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Intermountain Forest and Range Experiment Station

General Technical Report INT-99

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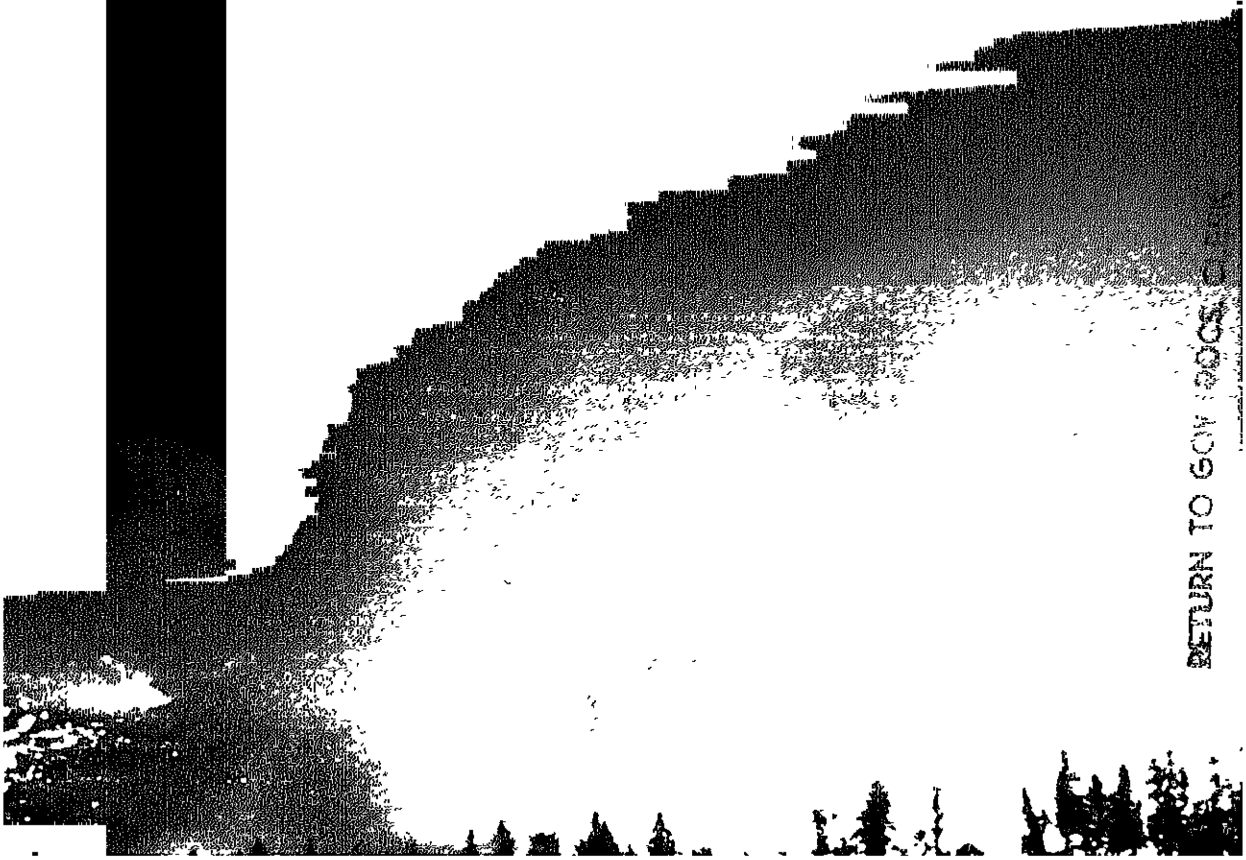
Clearcutting and Fire in the Larch/ Douglas-Fir Forests of Western Montana

A Multifaceted Research Summary

NORBERT V. DeBYLE



COVER PHOTO:

The square 10-acre units on the relatively gentle slopes at Miller Creek facilitated firing to obtain strong central convection columns on these broadcast burns, illustrated here with a nighttime fire during virtually calm conditions on unit S-8.

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NORBERT V. DeBYLE

THE AUTHOR

NORBERT V. DeBYLE earned a B.S. in 1953 and M.S. in 1957 from the University of Wisconsin, with major emphasis in soils and forest soils, respectively. In 1962, he was awarded a Ph.D. in forestry from the University of Michigan. Since 1961 he has been employed by the Intermountain Forest and Range Experiment Station, leading watershed management research at Reno, Nev., for 3 years and at Logan, Utah, for 11 years. In his present assignment at Logan with the aspen ecosystem unit, Dr. DeByle continues to study the impacts of wildland management practices and fire on soils and water resources.

ACKNOWLEDGMENTS

This summary report represents contributions from many people. Administrative guidance for the research came from a steering committee composed of Arthur Brackebusch, Samuel S. Evans, Jr., and Charles E. Hardy. Personnel on the Lolo, Flathead, and Coeur d'Alene National Forests facilitated sale preparation and a rigorous harvest and treatment schedule. Ray L. Managhan and Gary L. Cain were responsible for sale administration and prescribed burning. R. C. McConnel surveyed and mapped the soils. William R. Beaufait was the on-the-ground leader and coordinator of the research group, consisting of Rodney A. Norum, William C. Fischer, James K. Brown, Raymond C. Shearer, Robert D. Pfister, L. Jack Lyon, Peter F. Stickney, Norbert V. DeByle, and Paul E. Packer—all scientists of the Intermountain Station; and of Donald F. Adams and Robert Koppe from Washington State University, and Curtis H. Halvorson from USDI Fish and Wildlife Service. Thanks also go to the many technicians involved—especially Patrick F. Hartless, Gerald Voeller, and Bryan D. Williams. Michael A. Marsden and Roger A. McCluskey were responsible for much of the data reduction and analysis.

The Results section is written by the scientists most closely involved with each of the disciplines represented. These scientists and Beaufait deserve more credit, however, for providing much of the material that was incorporated into other chapters of this document. Without their help and without the encouragement and support of Beaufait, Norum, Fischer, and James E. Lotan, this publication would not have been possible.

Constructively critical reviews of this manuscript by Beaufait, Fischer, Halvorson, Koppe, Lotan, Norum, Packer, Pfister, Shearer, Stickney, and Clyde O'Dell are appreciated.

FOREWORD

Increased emphasis on comprehensive land management planning and more flexible fire management policies call for specific, quantified information on how fire affects resource production and the environment. Land managers must be able to predict and interpret biological and ecological responses to prescribed fire and wildfire for use in planning and management of forested ecosystems.

Dr. DeByle's summary report describes the specific effects of prescribed fire and wildfire in the western larch/Douglas-fir forests of western Montana. This study is significant because it considered an array of fire intensities and because it was conducted on an interdisciplinary basis. We are indebted to those who organized and directed such far-sighted effort. Art Brackebusch, Mike Hardy, and Sam Evans, together with Dr. William R. Beaufait, in particular are to be commended for their vision and professional dedication.

The paper should serve both land managers and specialists. It should help land managers make informed decisions in this increasingly complex world. The report will make managers more aware of possible consequences of clearcutting and burning and more capable of measuring these consequences than in earlier times.

Forestry specialists, certified silviculturists for example, will also benefit from the specific information useful in writing prescriptions and in assessing environmental impacts.

It is a particularly difficult task to write an integrated summary of an interdisciplinary study such as the one conducted at Miller Creek and Newman Ridge. Dr. DeByle is to be commended for his role in bringing us this paper.

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RESEARCH SUMMARY

Logging slash on 73 clearcuts in the western larch/Douglas-fir forest of western Montana was broadcast burned over a wide range of environmental conditions. A broad array of fire intensities and effects was achieved. A severe wildfire was also evaluated and compared to the prescribed fires. Fire effectiveness, especially for removing the duff layer, was measured and related to preburn conditions, fuel loads, and fire intensity. The effects of these treatments on air quality, forest regeneration, vegetative recovery and development, small mammal populations, soil physical and chemical parameters, and runoff and erosion were measured and analyzed.

Fine fuels contribute most to fire spread and intensity. Water content of fine fuels should be within 10 to 17 percent for safe and effective burning. If fuels are uniformly distributed, measurements of duff depth and of the water content of its lower half permit prediction of the amount of an area that will burn bare to mineral soil. Fire intensity influenced the height of smoke columns most, pushing some plumes 8,000 feet above the mixing depth. The smoke contained about 30 pounds of particulate matter for each ton of fuel consumed. After a good seed crop, conifer seed distribution on small (<15 acres) clearcuts was adequate, and germination was good on sites with one-half inch or less of residual duff. Seedling loss from summer drought was severe on south slopes, where practices to provide additional shade are recommended. Herbaceous cover increased rapidly after fire, peaking by the second or third postburn year. Shrubs did not predominate until at least the sixth year. Deer mice, chipmunks, and red-backed voles consume significant quantities of seed from conifers. Red-backed voles were most common in old-growth timber but virtually disappeared after clearcutting and burning. Deer mouse populations increased dramatically after intense fires. The treatments temporarily impaired soil protection and increased overland flow and erosion. However, vegetative recovery on all but the south slopes returned conditions to near prelogging status within 5 years. There was a flush of nutrients in overland flow and sediment during the first postfire year. The ash-duff layer lost nutrients and the surface mineral soil gained nutrients during the first 2 years.

CONTENTS

Beaufait viewing the logging operation at Newman Ridge in 1968.

INTRODUCTION

Broadcast burning of logging slash to reduce wildfire hazard and to prepare the site for planting began as early as 1910 in the western white pine type (LeBarron 1957). Today the use of prescribed fire is a well-established technique in Northern Rocky Mountain forests (Olson and Fahnestock 1955; Roe and others 1971). Although the use of fire to accomplish land management objectives in the West has been practiced for decades, the research described herein is the first known attempt to enlist several disciplines in an investigation of the effects of many broadcast fires, burned over a wide range of fuel and weather conditions, in the logging slash of western conifers.

This multidisciplinary research commenced in 1966 in the western larch/Douglas-fir forests of northwestern Montana by a team of scientists working in close cooperation with land managers. The effects of clearcutting, ground-lead skidding, and subsequent broadcast burning of the logging slash in these old-growth forests were evaluated from several perspectives. Fire behavior and amount of fuel and duff consumed were related to fuel and weather variables by fire scientists; smoke production and dispersion were studied by air quality engineers; seedbed preparation and establishment and growth of conifer seedlings were measured by silviculturists; successional development and amount of cover afforded by vegetation growing on the burns were traced through several years by plant ecologists; numbers and species of small mammals on treated and on control areas were quantified by a wildlife biologist; and physical and chemical impacts on soil and on runoff waters were determined by watershed and soil scientists. Most of the results within each of these fields have been published (appendix C lists publications). In this report, however, results of all disciplines are summarized and then discussed as an integrated body of research, with emphasis on findings of particular value to the resource manager.

Background

Fire is one of the driving forces in the Northern Rocky Mountain conifer forest ecosystem. Indeed, some forest types are considered to be fire dependent (Habeck and Mutch 1973). The western larch/Douglas-fir type is one of these. It is a seral type, usually growing as even-aged stands following wildfire. Fire kills some or all of the standing crop, opens up the forest, and creates a mineral soil seedbed, allowing tree regeneration. Hence, fire can be considered a natural part of this forest environment (Wellner 1970). This vegetation-soil complex has developed over thousands of years, with fire periodically perturbing the system.

During this century the value of these forests as a source of wood for our society was realized. This value has resulted in these lands being protected, when possible, from wildfire. Clearcutting has been a common method of harvesting timber. After harvesting, prescribed burning often is used to prepare mineral soil seedbeds and reduce the wildfire hazard created by logging residue (Steele and Beaufait 1969). Thus, to the extent possible, man has mimicked the natural role of wildfire in his management of this forest type.

Between 250,000 and 300,000 acres (100 000 to 120 000 ha) of forest are harvested annually in the Northern Rocky Mountain region of the United States. Most of these harvested acres require treatment to assure adequate natural regeneration or, alternatively, to prepare the site for planting. Resource managers are faced with the problem of adequately regenerating these stands with desirable species at a reasonable cost. Moreover, sites to be treated must be protected from wildfire, watershed damage, and potential reduction in soil productivity. Also, of increasing importance, atmospheric quality must be maintained in conformance with State and Federal air standards. Water quality, aquatic habitat, wildlife habitat, and amenity values must be maintained, too.

Of the several techniques for reducing fire hazard and preparing the clearcut for regeneration, prescribed fire is usually the most economical. Because it is easy to control and relatively inexpensive, dozer piling of logging debris and burning of these piles after autumn rains thoroughly wet the forest earlier was the most common use of prescribed fire in this region. As the technique was developed and accepted, and with increasing concern about equipment and energy costs, watershed protection, soil productivity, air quality, and natural amenity values, the use of broadcast burning of logging slash became widely applied. Approximately 10,000 acres (4 000 ha) of clearcut forest land are broadcast burned annually in this region. This represents most of the acreage now clearcut each year.

Based on interviews with foresters throughout the Intermountain West, Beaufait (1966b) characterized a successful broadcast burn as one that:

(1) consumed the duff to the extent of exposing mineral soil on 50 percent or more of the area burned, and (2) consumed all woody material up to about 6 inches in diameter. Prescribed broadcast burns have not always accomplished these objectives. As a tool for preparing sites for future crops, prescribed fire was found to produce erratic results in many areas (e.g., not enough seedlings in spruce forest types, too many in larch and lodgepole pine). Wikstrom and Alley (1967) found a large, unexplained variation in slash disposal and burning costs. It became important to relate such variation to silvicultural practices. Also, the practice of clearcutting coupled with the short fall burning period resulted in an increasing backlog of acres requiring treatment.

Probably the most important reason for prescribed burning failures is the variable nature of fire itself. Fire can burn over an area in an infinite number of ways. Intensity depends on fuel volume and moisture content as well as environmental conditions. Thus, fire is not a single treatment but rather a number of possible treatments. To be successful, the prescription and execution of a fire must be specific to a fuel bed, its moisture condition, and to at least one well-defined management objective (Fischer 1978).

Prescribed fires usually are conducted during safe burning conditions for the convenience of the responsible organization. Concern, unfortunately, is often centered on the fact of treatment rather than on the quality of treatment. Furthermore, emphasis is often placed on burning to reduce wildfire hazard, seedbed preparation being an expected side benefit. Although the wildfire hazard may be satisfactorily reduced by burning only the fine fuels, site preparation may not occur unless the duff also burns.

The need to improve the quality of prescribed burning accomplishment was recognized by land managers and research scientists alike. Consequently, the Northern Region and the Intermountain Forest and Range Experiment Station of the Forest Service jointly supported this study of prescribed fire and its use in forest management.

Development of This Research

Beaufait's survey (1966b) of prescribed burning in the Intermountain West provided insight into management problems. The survey indicated that greater use of broadcast burning and extension of the burning season into the spring and summer period would be necessary if forest management objectives were to be met. The increasingly steep sites being logged and the large acreages annually being cut precluded complete reliance upon the conventional method of "pile and then burn in the autumn" for meeting these objectives. Also, new personnel would have to be trained to accomplish the burning.

A need for better guidelines in the use of prescribed fire, particularly broadcast slash burning, as a silvicultural tool was recognized. After review of prescribed fire from both administrative and research viewpoints, a prospectus was written outlining participation of all concerned disciplines in a series of studies to be superimposed on a basic design to be developed by scientists at the Northern Forest Fire Laboratory. This prospectus was implemented in 1966. Highest priority was assigned to the western larch/interior Douglas-fir forest type growing on sites where subalpine fir is climax in the Northern Rocky Mountain region. In the autumn of that year the Miller Creek block, with some 60 cutting units, was laid out on the Flathead National Forest. After research was underway here, a replication was established in 1968 on Newman Ridge on the Lolo National Forest. (For simplicity and ease of reading, these two cutting blocks are usually referred to as Miller or Newman, respectively, throughout the remainder of this paper.)

Fortunately, fire research techniques developed over recent years permitted successful instrumentation of, and data gathering from, the chosen study blocks at Miller and Newman. Recent research attention to the nature of fuels and the behavior and intensity of fire itself was especially important at this point in time.

Measurements of slash fuels and the behavior of slash fires made by Olson and Fahnestock (1955), Fahnestock (1960), and Fahnestock and Dieterich (1962) provided a basis for quantifying potential energy sources in the use of fire for silvicultural and other land management purposes. Other forest fire researchers began characterizing natural forest fuel beds by the amount of work accomplished by prescribed fires. Using Byram's (1959) equations for energy release rate, Van Wagner (1965) compared the effects of burning at four fuel levels. He applied head fire intensity data to tree crown and stem damage, seedbed preparation, and subsequent regeneration. As fire intensity increased, both mineral soil exposure and seedling success improved. Similar results were reported by Buckman (1962, 1964) and by Beaufait (1960, 1962). More recently, laboratory studies of fire behavior in forest fuels

developed a foundation for characterizing fires under natural conditions. Building upon the work of Thomas (1958, 1963), Rothermel and Anderson (1966) modeled fuel beds and stressed the importance of energy release rate for describing fire intensity and behavior.

Between 1963 and 1965, a series of 2- to 4-acre (approximately 1 - to 2-ha) areas were inventoried and broadcast burned in Douglas-fir slash on the University of Montana's Lubrecht Experimental Forest. This was perhaps most applicable to the planned research at Miller and Newman. These tests provided: (1) a quantitative comparison of site and early vegetative succession after replicated fires in two spring and two autumn seasons, and (2) successful instrumentation for evaluating burn quality, fire intensity and spread, fuel volume and moisture content, and ignition and control methods (Steele 1964; Steele and Beaufait 1969).

Objectives

The principal purpose for this research was to develop criteria by which prescribed broadcast fires in logging slash could be scheduled to best meet site preparation, hazard reduction, and other management goals. Objectives of the fire research phase were: (1) correlate a wide range of fuel and weather conditions with amount of duff reduction and mineral soil exposure; (2) predict prescribed fire smoke column height from fuel conditions and environmental factors; (3) provide a design and field layout upon which studies by cooperating scientists from other disciplines could be superimposed.

Fire effects literature usually contains a grossly inadequate quantification of the fires involved. Fire intensity is often characterized as being "high" or "low" based only upon the investigator's experience. This study design provided an unparalleled opportunity to correlate fire effects with quantified fires conducted over a wide range of fuel and environmental conditions. Taking advantage of this opportunity, studies with the following goals were conducted:

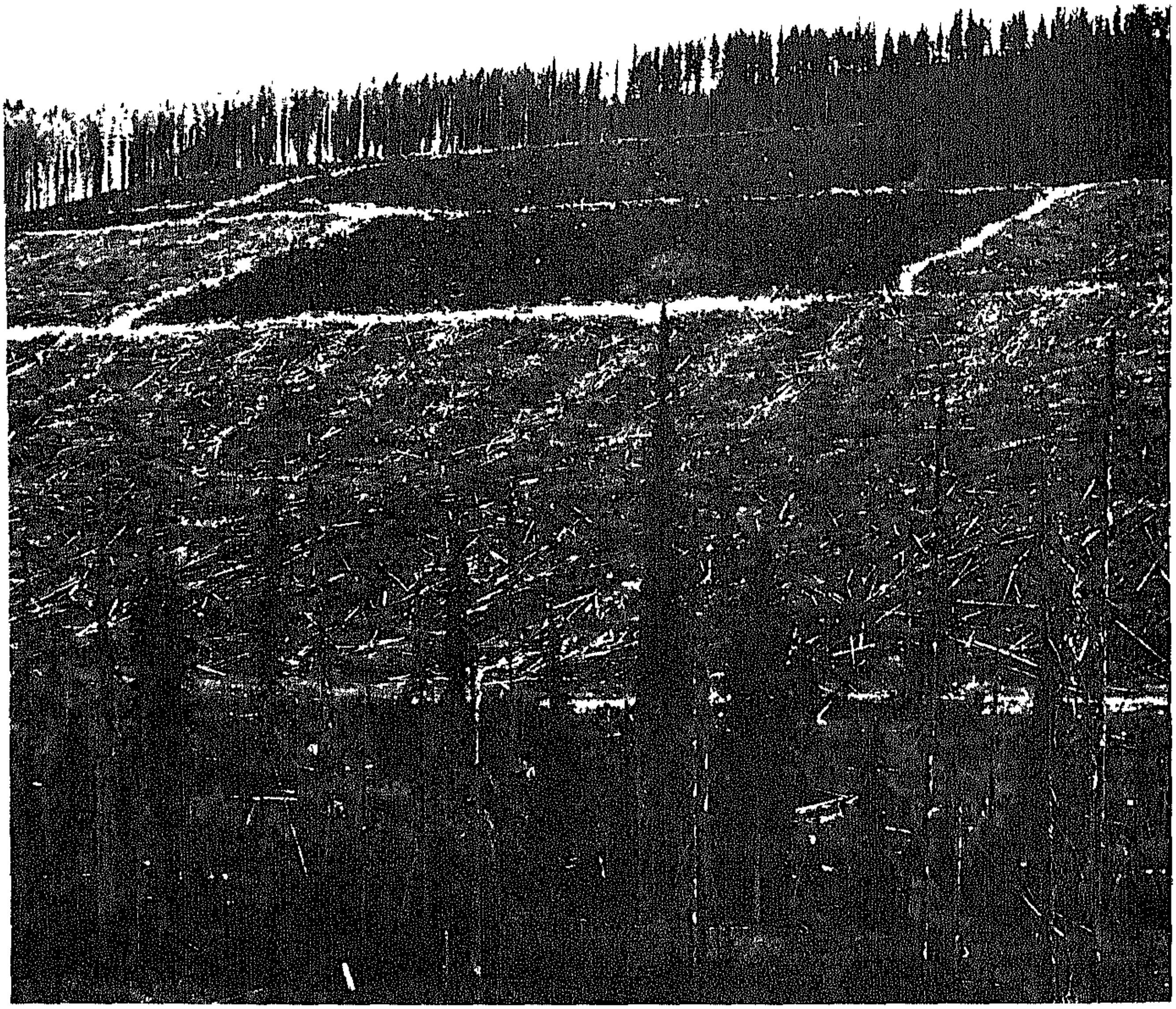
The air quality and smoke management study objectives were (1) to determine the range of combustion product emissions from a series of fuel moistures and meteorological conditions, and (2) to monitor the movement and dispersal of these emissions.

The overall silvicultural research objective was to determine how regeneration of selected conifers was influenced by seedbed condition and other site factors following prescribed fires in clearcuts. These results were contrasted with nearby uncut areas burned by wildfire or slashed but unburned clearcuts.

The plant ecology objective was to describe in quantitative terms the development of seral forest communities following the clearcutting-burning treatment, and to determine the influence of prelogging vegetation and fire on vegetal development patterns.

Small mammal populations were studied to (1) determine animal species composition and relative abundance on uncut and clearcut/burned areas, and (2) to relate mammal succession patterns to plant succession after clearcutting and broadcast burning.

The watershed and soils objectives were: (1) to determine which vegetal, soil, and topographic factors affect overland flow and soil erosion, (2) to measure the effect of varying intensities of broadcast burning on overland flow and erosion, (3) to develop means for predicting expected overland flow and erosion after burning under selected prescribed conditions, and (4) to determine the changes in soil chemistry and fertility, the quality and nutrient content of overland flow, and the plant nutrient losses from these sites as a result of the clearcutting and quantified broadcast burning treatments.



A series of north-facing units at Miller that have been logged; three units (N-5, -11, and -12) were burned the season prior to this photograph. (Washington State University photo)

AREA AND STUDY DESCRIPTIONS

Site Description

The Miller block is on the Miller Creek and Martin Creek drainage near Olney, Mont. (48°31' N. latitude, 114°43' W. longitude); the Newman block is approximately 100 miles (160 km) southwest, on Newman Ridge between Two Mile Creek and Ward Creek, near St. Regis, Mont. (47°17' N. latitude, 115°17' W. longitude) (fig. 1.). A combined total of 76 treatment units were located on both blocks—sixty 10-acre (4-ha) units at Miller; 16 units, ranging from 20 to 58 acres (8-24 ha), at Newman (figs. 2 and 3).

The elevation at Miller ranges from 4,200 to 5,000 feet (1280-1524 m). Slopes average 24 percent and range from 9 to 35 percent. Soils have developed in glacial till from the argillites and quartzites of the Wallace (Belt) formation and are mantled with a thin layer of loess. They belong to the Sherlock soil series and, for the most part, are Andic Cryoboralfs having an unincorporated surface organic horizon from 1 to 3 inches (2-8 cm) thick. The surface 1/2 to 1 inch (1-3 cm) of mineral soil is silt loam of single-grain structure (30 percent sand, 56 percent silt, 14 percent clay). This overlies a foot of gravelly loam with a weak blocky structure, beneath which is very stony loam to a depth of at least 6 feet (2 m).

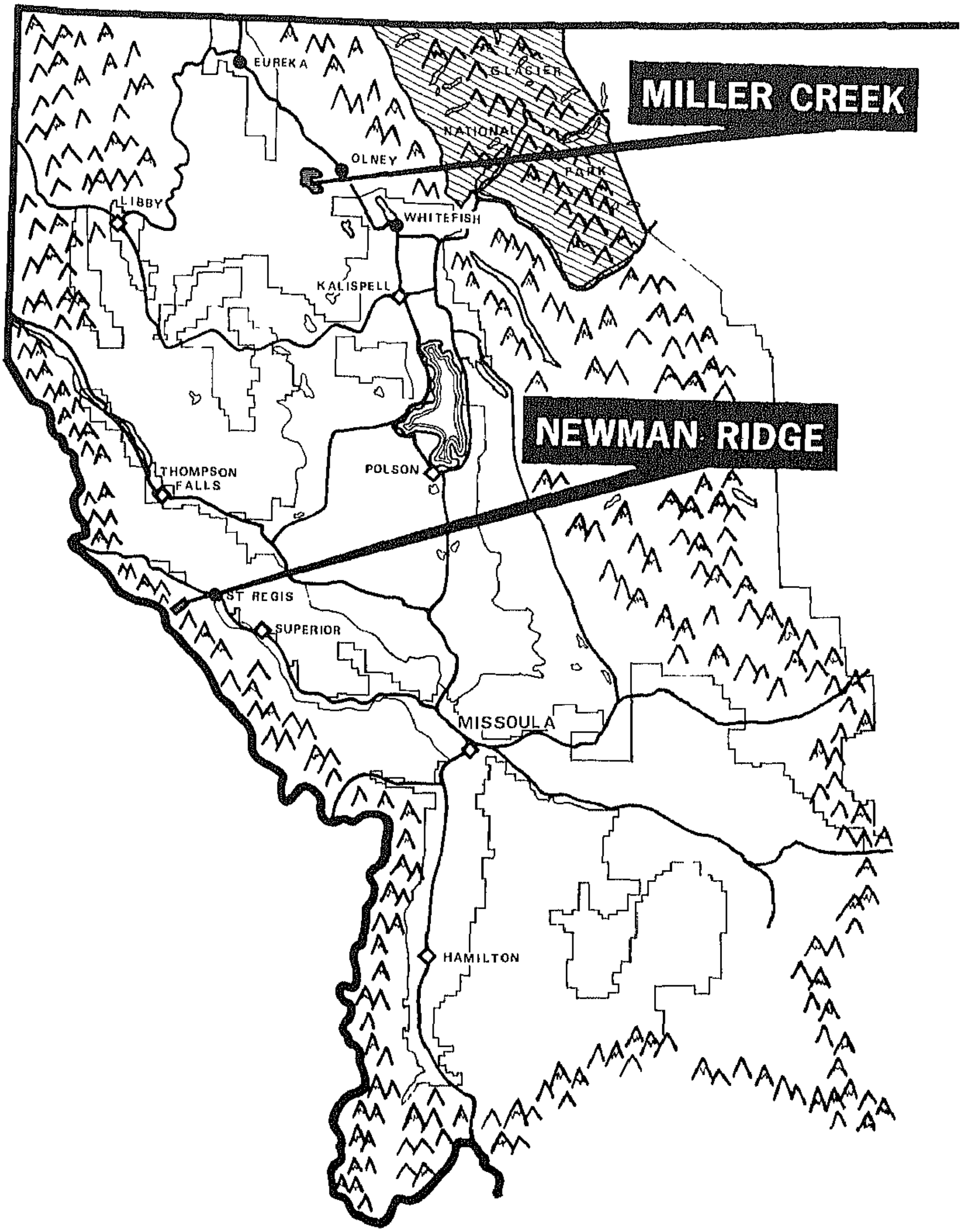


Figure 1.—Location of Miller and Newman study sites in northwestern Montana.

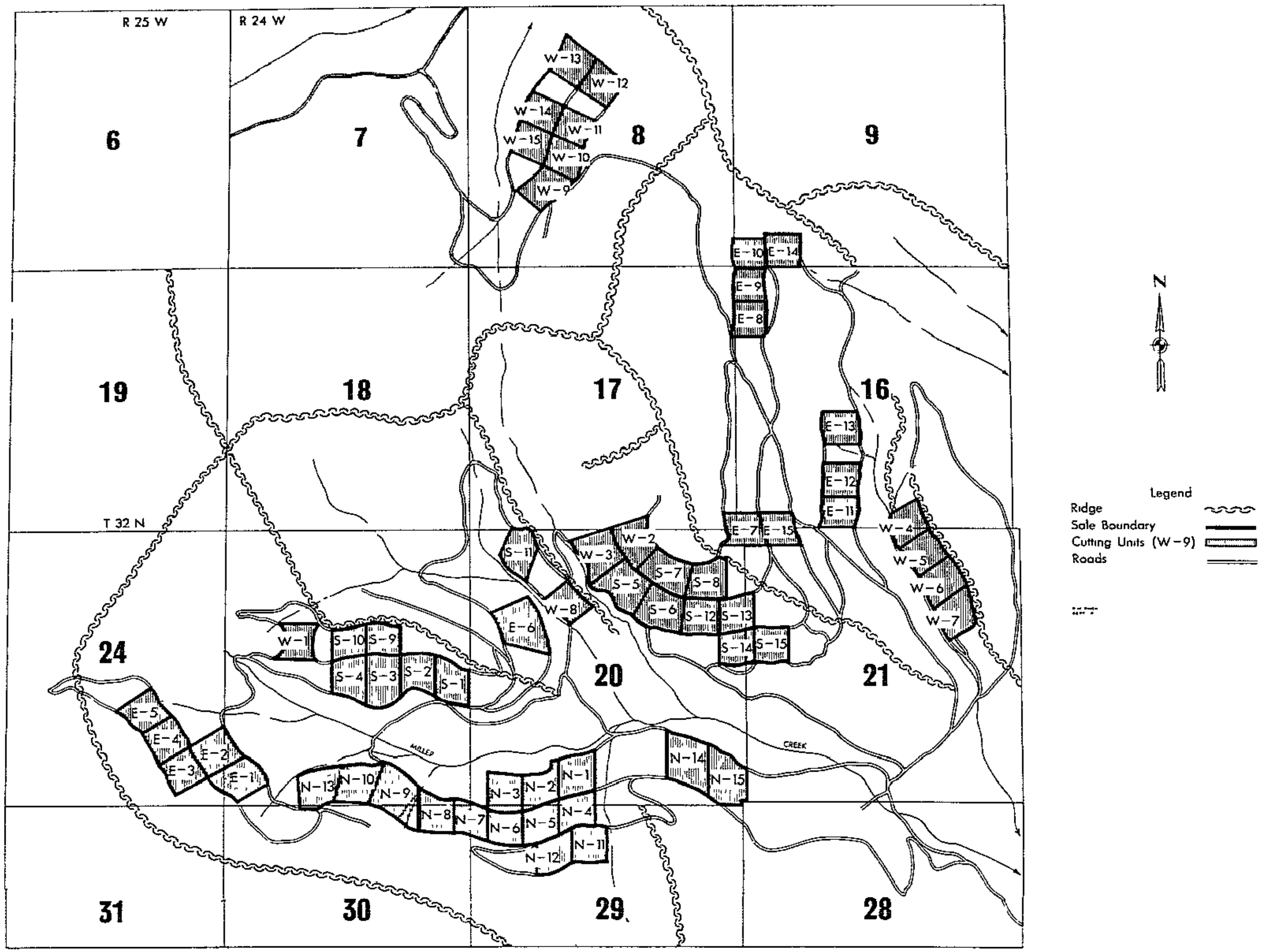


Figure 2.—Layout of 10-acre units at Miller.

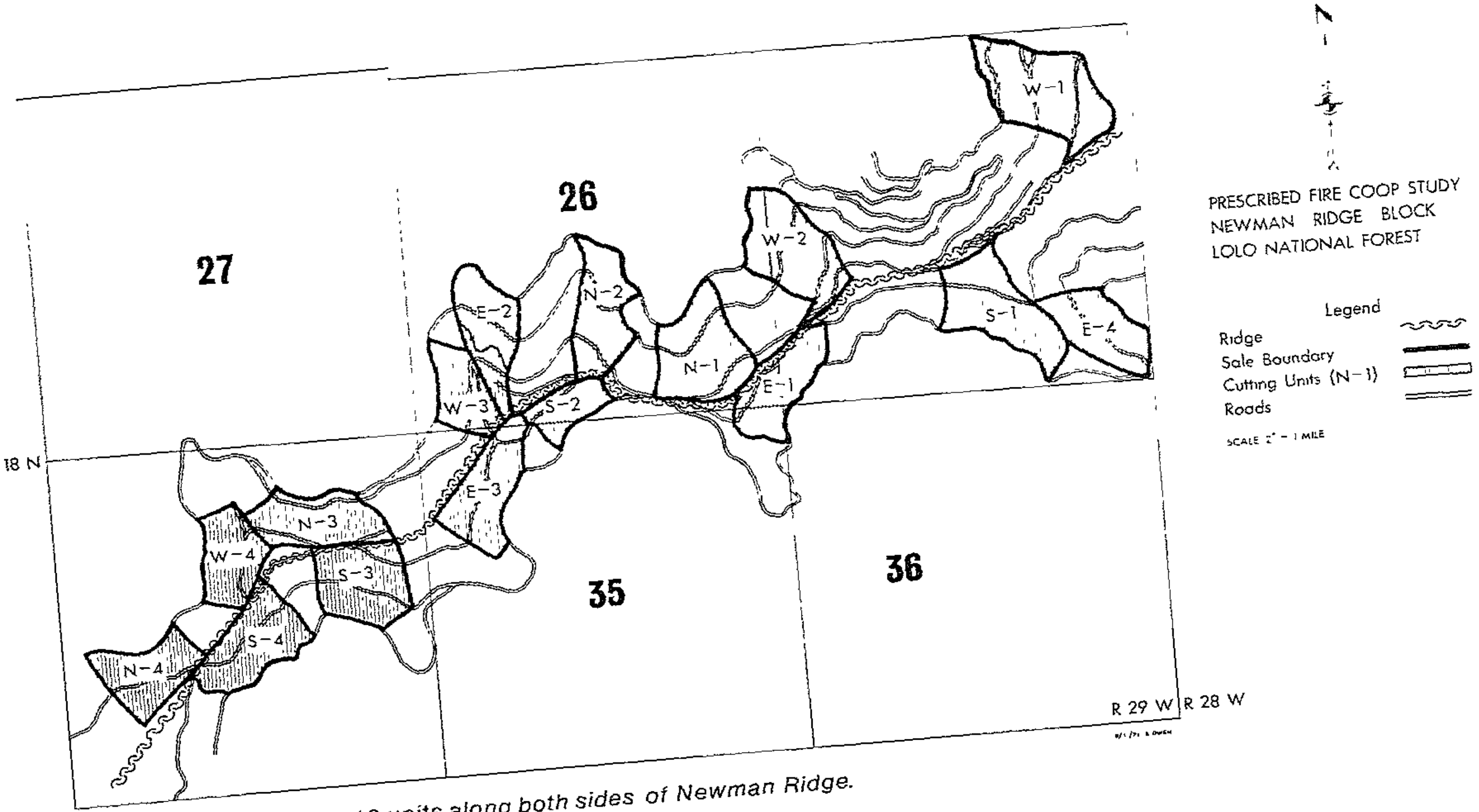


Figure 3.—Layout of the 16 units along both sides of Newman Ridge.

The Newman study area is slightly higher, elevations range from 4,400 to 5,400 feet (1 341-1 646 m) and much steeper (mean slope of 55 percent, ranging from 44 to 76 percent) than Miller. Soils have developed in place or in colluvium from argillites and quartzites of the Belt formation. The surficial loess deposit at Miller is 1/2 to 2½ inches (1-6 cm) thick; on Newman it is 2 to 3 inches (5-8 cm) thick. Ash from the Mt. Mazama and Glacier Peak volcanic eruptions occurs in this loess (Fryxell 1965); the remainder of the deposit probably comes from the Palouse region in eastern Washington. The texture of the surface 2 inches (5 cm) of soil on Newman is silt loam (29 percent sand, 58 percent silt, and 13 percent clay). These soils belong to the Craddock series and classify as Andic Cryochrepts.

Both the Miller and Newman areas characteristically have long, cool, wet winters and short, dry summers. Annual precipitation averages about 25 inches (64 cm) at Miller and nearly 40 inches (102 cm) at Newman; approximately two-thirds falls as snow. Although high-intensity summer rainstorms occasionally occur, most rain falls at low intensities from Pacific maritime frontal systems. The most rainfall comes during April, May, and June, the months when snowmelt runoff is greatest. These are humid watershed lands, which yield more than 10 inches (25 cm) of streamflow annually, nearly all as yearlong seepage flow (Packer 1959). When plant cover is sufficient, only a small part of the annual precipitation becomes overland flow. Most of it contributes to seepage flow or is stored in the soil mantle and thus reduces soil water deficits created by evapotranspiration.

The vegetation on both blocks was classified according to forest cover type (Society of American Foresters 1954) and habitat type (Pfister and others 1977). The cover types identified were. larch/Douglas-fir, grand fir/larch/Douglas-fir, ponderosa pine/larch/Douglas-fir, lodgepole pine, and Engelmann spruce/subalpine fire. The larch/Douglas-fir type occupied well over 50 percent of the area. With typical variation due to exposure, Miller timber volumes were almost evenly divided among western larch, interior Douglas-fir, and Engelmann spruce. Newman produced little spruce, but had a greater variety of species, including some ponderosa pine and western white pine. Lodgepole pine and true firs had significant volumes in both blocks. The Miller stands were 200 to 250 years old, those on Newman 180 to ?00 years old. The volume of commercial tim-)er harvested from these blocks is summarized in able 1.

Table 1.—Commercial timber volumes harvested (Scribner Decimal C)

Species	Miller Creek (641 acres)		Newman Ridge (526 acres)	
	M bd.ft./ acre	Percent of total	M bd.ft./ acre	Percent of total
Larch	6.4	25 7	5.1	26.4
Douglas-fir	7.5	30.6	6 5	33.6
True fir	1.6	6 5	1 4	7.3
Spruce	7 6	31 1	0.6	2 8
Lodgepole pine	1 5	6 2	3.3	16.9
Ponderosa pine	0	0	1.7	8.8
White pine	0	0	.6	2.8
Cedar	0	0	.3	1.4
Total	24.6	100.0	19 5	100.0

The Miller block, with a relatively uniform, cool, moist environment, consists largely of only one habitat type (h.t.), *Abies lasiocarpa/Clintonia uniflora.* Three phases of this h.t. are represented: *Menziesia ferruginea* phase on the colder middle and upper north and east slopes, *Xerophyllum tenax* phase on the drier south and west aspects, and *Clintonia uniflora* phase on the remaining sites. Cool, moist stream bottoms were mapped as *Thuja plicata/Clintonia uniflora* h.t. (fig. 4).

In contrast, on Newman Ridge seven distinct habitat types were identified, from a warm and dry *Pseudotsuga/Physocarpus* h.t. to a cool and moist *Thuja plicata/Clintonia uniflora* h.t., *Menziesia ferruginea* phase. This variety of types was reflected in the broad vegetal diversity which occurred across this ridge. The seven types represented were: *Abies grandis/Clintonia uniflora* h.t., on concave east, northwest, and protected south-facing slopes; *Abies grandis/Xerophyllum tenax* h.t. on upper west-facing slopes; *Thuja plicata/Clintonia uniflora* h.t., *Menziesia ferruginea* phase on concave north and northeast aspects; *Pseudotsuga menziesii/Vaccinium globulare* h.t., *Xerophyllum tenax* phase on upper south-facing slopes; *Pseudotsuga menziesii/Physocarpus malvaceus* h.t., *Physocarpus malvaceus* phase on convex southwest slopes; *Abies lasiocarpa/Clintonia uniflora* h.t., *Menziesia ferruginea* phase on north slopes along the ridge lines; and *Abies lasiocarpa/Xerophyllum tenax* h.t., *Vaccinium globulare* phase on south slopes along the ridge line (fig. 5).

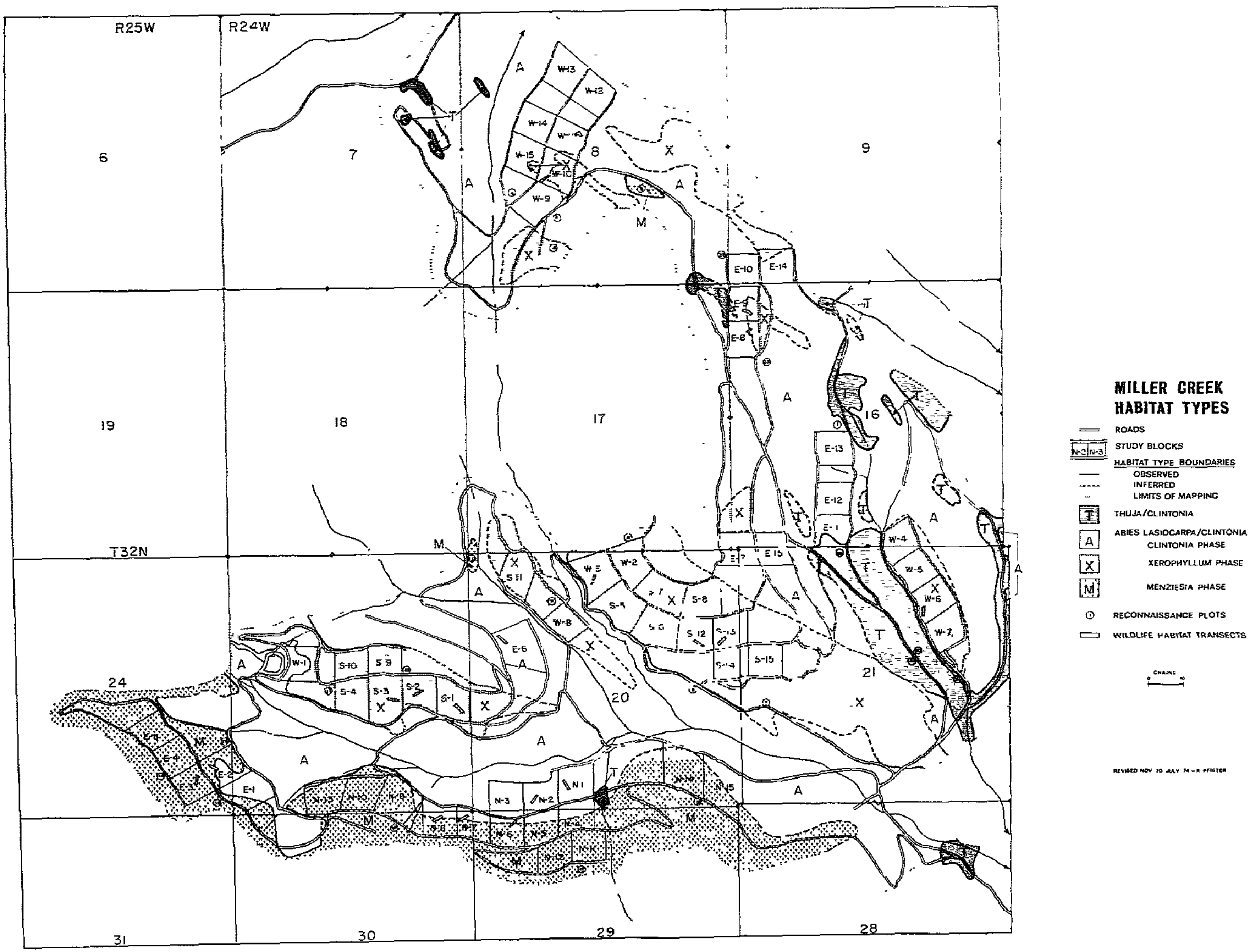


Figure 4.—Hat ' ıs at Miller.

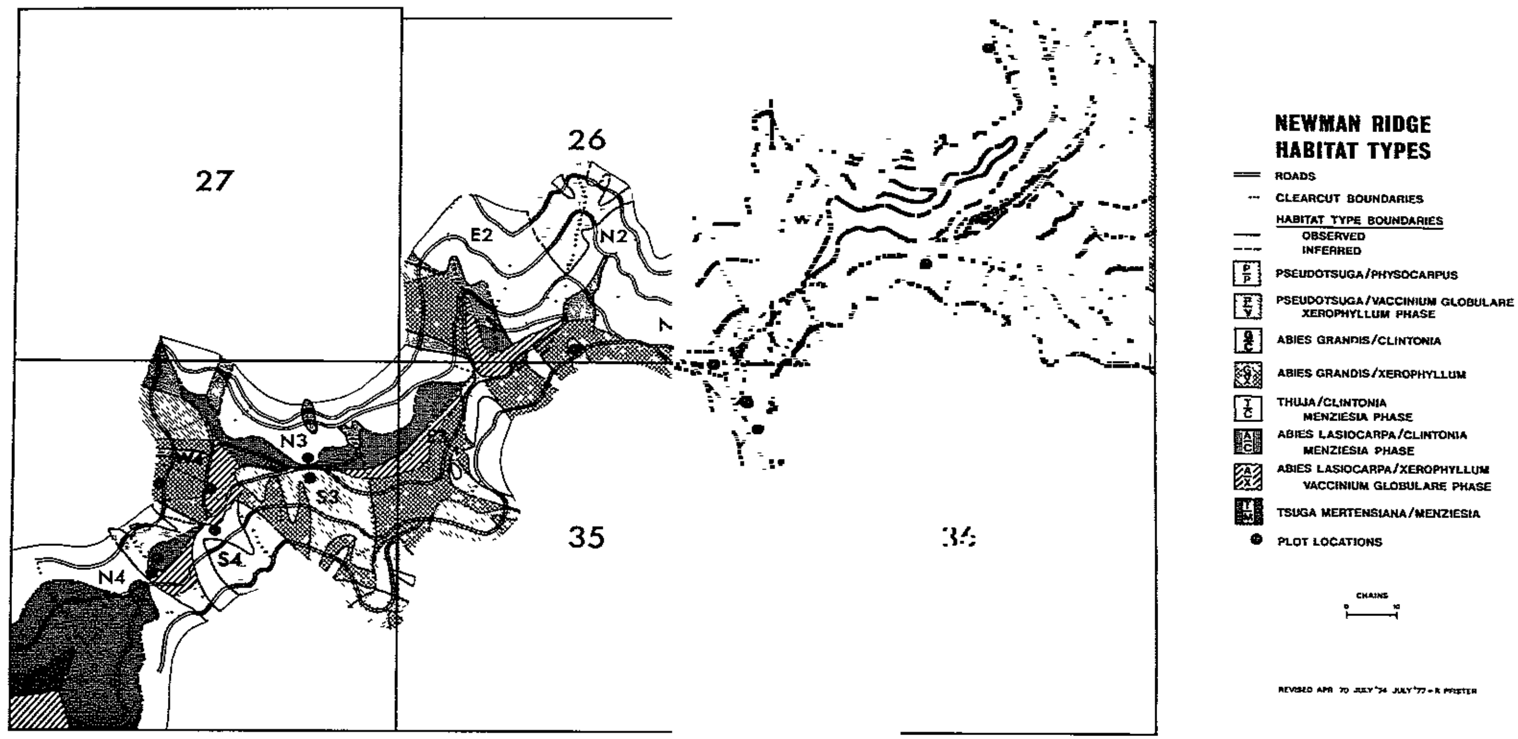


Figure 5.—Habitat types at Newman.

Preburn fuel loads, excluding duff, varied from 60 to 165 tons/acre (14-37 kg/m^2) among individual units. Miller units supported slightly greater slash loadings than those at Newman—114 tons/acre compared to 104 tons/acre (25 kg/m^2 vs. 23 kg/m^2). Size distribution was quite similar. Approximately 88 percent of the slash fuel weight was greater than 4 inches (10 cm) in diameter; 10 percent was 0.4 to 4 inches (1-10 cm) in diameter; and 1 percent each was twigs and needles (Beaufait and others 1977). Duff weight on individual units varied between 4 and 50 tons/acre (0.90 and 11 kg/m^2) at Miller and between 15 and 29 tons/acre (3 and 7 kg/m^2) at Newman. Average duff weight at Miller was 26 tons/acre (5.9 kg/m^2) compared to 23 tons/acre (5.1 inches (5.45 cm) at Miller and 2.05 inches (5.22 cm) at Newman (Beaufait and others 1977).

Study Design

The 60 units at Miller Creek and the 16 at Newman Ridge were each laid out in an orthogonal design, with equal numbers generally facing each of the four cardinal aspects.

A square plot, 2½ acres (ca. 1 ha) in size, in the center of each Miller unit was used for much of the sampling. Three similar plots were laid out in each of the Newman units (fig. 6).

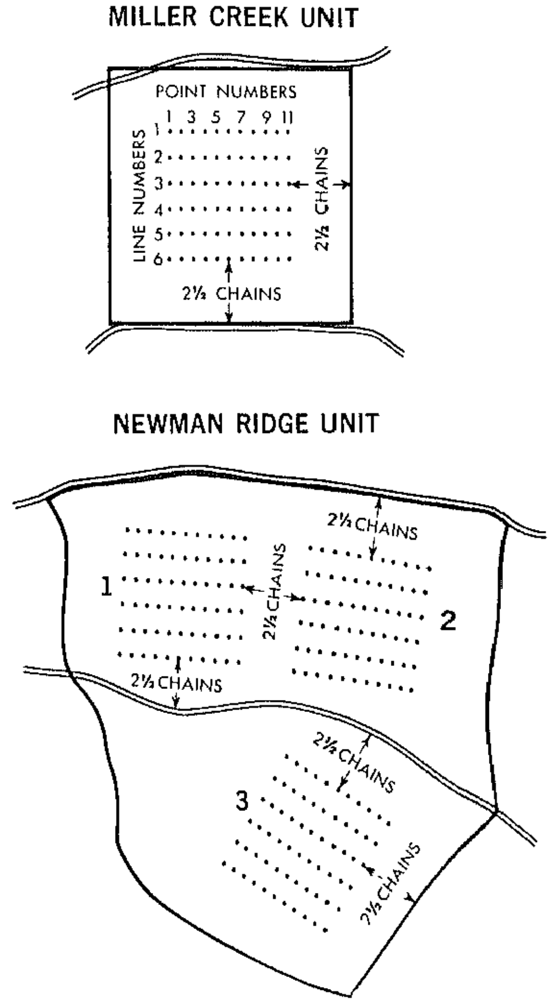


Figure 6.—Plot layout and sampling point locations on typical units.

The study plan called for an equal number of fires, in similar fuel loadings, on all aspects, in the spring, summer, and autumn for 2 years (1967 and 1968) at Miller and 1 year (1969) at Newman (Beaufait and others 1977). The ideal of complete orthogonality was not achieved. A wildfire in August 1967 at Miller burned several south-, east-, and west-facing units, creating an imbalance in the original design. Also, concern for fire control further compromised the design: units with heavy fuel loading were burned under wetter conditions than those with light loading. A total of 73 sample plots in 55 different units were burned and the data used in subsequent analyses. Of these, 11 sample plots were burned in the spring, 51 in the summer, and 11 during the autumn. The treatment record over the 3 years probably represents the realistic range of prescribed burning opportunities in the Northern Rocky Mountains.

Methods

The design required that fuel loads be spread as uniformly as possible across each unit, which also enhanced fire spread if burning conditions were less than ideal. To accomplish this, directional felling and double-drum jammer skidding was used. The jammer roads were spaced at least 600 feet (183 m) apart. No machine operation was allowed within the 2.5-acre sample plots. After felling and skidding were completed, a slash crew dropped all remaining stems, thus enhancing fuel bed uniformity wherever possible. Slash was allowed to dry and weather before burning. Average slash curing time was 9 months, but ranged from less than 2 to almost 18 months on the burned units from which data to meet the objectives of this research were gathered. Eight units not burned remain as controls for long-term comparison of treatments. A few units were burned up to 3 years after harvest. Four units at Miller were not logged before being swept by the August 1967 wildfire. Two of these on a south slope, adjacent to slashed units that were burned at the same time, remain a valuable comparison of fire in standing timber versus fire in logging slash.

The sampled plots were burned over a range of conditions during the years of 1967-1970. The fuel treatment schedule and tabulated burning conditions may be found in Beaufait and others (1977).

Anticipated fire behavior was the main consideration in determining if a unit was ready to burn. Fuel moisture was to be within a range where the fire could be expected to burn the entire unit and weather had to be favorable enough to permit containing the fire within the designated unit. Fuel water content and weather were continuously monitored to evaluate a unit's readiness to burn. Weather stations were operated throughout the snow-free seasons at Miller and Newman close to the clearcut units. Weather records were used to compute fire-danger buildup index (USDA Forest Service 1964) during the June through October seasons, when fires were conducted at Miller in 1967 and 1968 and Newman in 1969. In addition, to measure annual precipitation for watershed research, a storage gage was maintained at each study site for several years. As part of the silviculture research, three additional weather stations were operated at Newman Ridge from 1969 through 1974. These measured air temperature, relative humidity, and amount and direction of air movement on north- and south-facing clearcuts and the intervening ridge from June to October of each year.

To attain the fire research objectives, each unit was sampled to determine depth and weight of duff; amount, size, and kind of fuel potentially available; water contents of duff, fuel, and soil at fire time; and amount of heat experienced during the fires

The duff was quantified by weighing a large number of cylindrical duff samples of known volume and depth. Ratios of dry weight to depth were used to develop equations for predicting duff weight from preburn and postburn measurements of duff depth. The weight of duff per unit of depth was found to be different for different exposures (Beaufait and others 1977). Duff depths then were measured both before and after burning on at least 72 points on each study plot.

The amount of dead and down woody slash fuels was measured on 66 points on each plot using a planar intersect sampling scheme, with 3P subsampling as reported by Beaufait and others (1974). This method is similar to that described by Brown (1974), and could be simulated by following Brown's method of inventorying down woody material. The fuel loadings are tabulated in detail by size class and fuel type in Beaufait and others (1977).

Fuels, duff, and surface mineral soil were sampled on each site immediately prior to burning and their water content determined. A combination of ovendrying and titrimetric methods was used to measure the water contents.

Weight loss from 36 water can analogs per study plot (Beaufait 1966a) was used to sample heat pulse to the site during each fire. These analogs indicate the total amount of heat experienced at the point of measurement; they do not truly measure fire intensity in terms of energy release rate on an area. The amount of water lost from these analogs was significantly related to the water content of the upper half of the duff layer and to buildup index as reported by Beaufait and others (1977). Water can analogs are of little use to managers, but do serve a purpose in fire research by indicating relative intensity among fires.

The air quality and smoke management phase of this research was accomplished by employing three methods: (1) Continuous measurement of air quality was made at ground level at five points within 30 miles (48 km) of the burned units. (2) Smoke and carbon dioxide concentrations, elevations, and drift patterns were measured from selected fires with an aircraft. (3) Samples of slash and duff fuel were analyzed and were burned under controlled conditions in the laboratory and the emission products quantitatively determined.

The five ground level stations were operated for part of the 1967 and all of the 1968 fire seasons at Miller. Their specific locations are shown in figure 7 in the Results section.

Aircraft monitoring of smoke plumes from fires conducted during daylight hours was possible. For these, the aircraft flight tracks were of three types: (1) circling and penetration of the smoke column rising above the fire, (2) circling outside the column to observe and measure the rate of plume rise during the early phases of burning, and (3) intercepts of the altitude-stabilized smoke plume as it drifted downwind from the fire. The plumes were tracked and concentrations of carbon dioxide (CO_2) and particulates were monitored with onboard instrumentation—a CO_2 gas analyzer and a nephelometer. The latter measures light scattering from particulates, which, in turn, is proportional to particulate concentration (Charlson 1968).

The height of smoke columns from 22 fires at Miller was measured. These heights were, among other things, correlated with atmospheric mixing

depth, obtained through standard radiosonde ascents made locally immediately before each fire.

Instrumented "burning tables" in laboratories at the University of California (Riverside) and Washington State University (Pullman) were used to burn samples of several pounds and 3.5 oz (100 g), respectively, and to analyze the particulate, carbon monoxide, and carbon dioxide emission rates. The data from these analyses, though useful, had to be used with caution because fire characteristics and intensity on a burning table are far different than those observed in the field.

The silvicultural research required measures of soil water content, soil temperature, root mortality, duff reduction, seedbed condition, conifer seed production and dispersal, seedling establishment, natural regeneration, and survival and vigor of planted trees.

Water content of the surface 4 inches (10 cm) of mineral soil was measured gravimetrically before and after burning. These were supplemental to the duff water contents taken by the fire scientists. The temperatures reached during burning were approximated to a 6-inch (15-cm) depth into the soil at 36 points on each unit with the use of asbestos strips treated with temperature fusible paints (Shearer 1975). Also, duration of soil temperature maximums was recorded at a few selected points with thermocouples buried at four depths, down to 1.6 inches (4 cm). Root mortality of nonconiferous vegetation was sampled at six points within each unit using a chemical test developed by Hare (1965). Relationships among root mortality, soil water content, and soil heating were tested and reported by Shearer (1975).

Seedbed condition was categorized on subplots in each treated unit after burning. Seed crops of the primary tree species were estimated. Production and dispersal of conifer seed at Newman were sampled from 1969 through 1974 and related to climatic and other variables.

Germination of conifer seed sown on typical postfire seedbeds was tested for several years on both blocks. Season, weather, and, particularly, duff depth were correlated with germination and survival. In addition, natural regeneration was tallied on plots at both Miller and Newman.

Though the results are not reported in this publication, 13 units at Miller and 7 units at Newman were planted with selected conifer species over a span of several years. Survival and vigor of this planted stock are being monitored.

Recovery and development of vegetation after the clearcutting and burning treatment were monitored on 20 units, 14 of them at Miller, the remaining 6 at Newman. Two permanent 16- by 82-foot (5- by 25-m) transects per unit were inventoried before and after treatment and continue to be sampled through time. Nested plots within these transects were used to sample different vegetational components. Tree basal area was measured and density of trees and shrubs per unit area was counted. Frequency of occurrence of herb and low woody plant species was determined. Cover (areal crown area) and volume (crown area × height) were measured or estimated for all vegetation components. Also, the amount of exposed surface not covered by vascular plants was estimated in the categories of rock, moss, litter, or bare ground. The largest plots (16 by 16 ft) were used for trees. The smallest (1.6 by 1.6 ft or 0.5 by 0.5 m) were used for herbs, small shrubs, and ground surface estimates. Individual species occupying a sixth or more of the plot were tallied.

Small mammals were trapped in the autumn of each of several years to ascertain population size and species composition as affected by treatment. The methods differ between areas. Kill-traps were employed at Miller—permitting population trends to be evaluated between years and treatments. At Newman live trapping furnished estimates of population densities.

In each sampled unit at Miller, 60 Museum Special kill-traps were placed in two parallel lines, with 10 trap stations in each line. These were baited with a peanut butter and oatmeal mix and set for 3 days of each year. Trapping began prior to logging in 1967 and continued through 1976, with 5 to 11 units being sampled each year. Results are expressed as numbers caught per trapping effort, with the trapping effort at Miller being 180 trap-nights per unit per year.

Newman was sampled with Sherman live-traps on two units (N-3 and S-3) and in two areas of adjacent undisturbed forest for 8 years (1969-1976). On each site, a 4.6-acre (1.9-ha) grid of 81 traps was used for 5 days annually. New animals caught in the 5-day period were marked and released, and population densities computed (Stickel 1954). A sampling of 1,620 trap-nights annually gave relative populations for comparison to results from the kill-traps at Miller.

Many soil physical and chemical characteristics as well as other parameters important to watershed behavior were sampled for several years at

both Miller and Newman. Batteries of runoff plots were installed on each block, two plots per cardinal aspect in the burned units and one plot per aspect in the nearby undisturbed forest. Overland flow and sediment were caught in tanks below the 12 plots at Miller from 1967 through 1971 and again in 1974, and below the 12 at Newman from 1969 through 1972, 1974, and 1975.

Soil bulk density and total pore space measurements were obtained from soil cores. Soil organic matter content, particle-size distribution, and water-stable aggregation were measured from bulk soil samples taken within each plot. Measurements of live plant cover and litter were obtained with a point analyzer on 200 points established on transects within each plot. Total overland flow and eroded material were measured each year following spring snowmelt runoff, after each major high-intensity summer rainstorm, and in fall before the onslaught of winter. Nutrient contents of this water and sediment were analyzed for 4 years from Miller and for 2 years from Newman.

In addition to the data taken from the runoff plots, bulk soil samples were dug from 10 selected points within the central plots on 35 Miller units. The chemical characteristics of this surface foot (30 cm) of soil were determined before burning, after burning, and for 2 years thereafter. The parameters measured were pH; total contents of nitrogen, phosphorus, potassium, sodium, calcium, and magnesium; available phosphorus; cation exchange capacity; and exchangeable and soluble potassium, sodium, calcium, and magnesium. Only sufficient sampling was done at Newman to chemically characterize the soils there, not to measure the effects of treatment. Chemically, the Newman soils were found to be similar to those at Miller.

Water repellency was tested on most soil samples gathered from both blocks, and was also examined in the field at Newman.

Application of Results

Site, stand, habitat, and treatment descriptions are given so informed judgment may be used in the application of these research results. The forest environment continuously changes through space. Many facets of this environment were studied here. The more facets being considered, the more obvious environmental variability becomes, and the more difficult becomes the complete transfer of research results to another site.

The quantities cited in the results of this research often will apply only to the studied site; but the general relationships pointed out should apply widely. The same principle holds for the presence of plant or animal species. Other species may occupy similar niches in environments geographically removed from western Montana and may respond to treatment very much like those at Miller and Newman. The results from some disciplines, such as air quality management, will apply more broadly than will the results from others, such as silviculture.

It is up to the manager to decide if the results from this work may be partially or wholly applied to the set of conditions with which he is working. After reading the description for Miller and Newman and mentally comparing it to the site and treatment of concern, the manager on the ground must answer the following: Are the results applicable here? What results may apply? To what extent? Can I extrapolate the numbers to my situation? Or, do only the general relationships apply? The following guidelines may help this hypothetical manager answer these questions.

The results are applicable to clearcut sites in western Montana and surrounding States and Provinces with similar geology, soils, forest types, and habitat types if similar loads of logging residue are broadcast burned. Extension beyond this limited area requires careful judgment.

The predictions for duff reduction and exposure of mineral soil by fires are broadly applicable if fuels (broadcast conifer slash), surface organic horizons on the mineral soil, weather, and fuel moisture contents are similar. These may occur from Alaska to Arizona, from eastern Washington to Siberia. Wide application is possible because essentially only physical principles are involved and the effects of treatment are immediate. Neither biotic diversity nor the later action of weather or biological processes complicate the prediction.

The same holds for smoke management. These principles apply worldwide. The cited values for carbon dioxide, particulates, and height of smoke columns ought to be applicable to broadcast burning of conifer logging debris on areas of corresponding size in mountainous or very hilly terrain anywhere that fuel and climatic conditions are like those at Miller and Newman.

The silvicultural findings are more restrictive; they cannot be so widely applied. Both physical

and biological processes are involved, and treatment effects may not be apparent for many years. Many more actions and interactions take place among a multitude of variables over a longer time to produce a given set of results than is the case for fire baring mineral soil, or for smoke rise and dispersion. Therefore, accurate prediction of long term silvicultural effects is risky. Nevertheless, the general aspects of conifer seed dispersal into openings, germination and survival of seedlings of these species on similar seedbed conditions, and the factors causing seedling mortality should apply quite broadly to the larch/Douglas-fir forest type. To fit the results more finely requires consideration of habitat types as well.

Vegetative development through the years after clearcutting and broadcast burning follows a seral pattern of herb to shrub to tree stages in many forest types. The time elapsed to progress from one stage to the next and the species involved in each stage will depend upon soils and climatic factors as well as upon plant geography and ecology. A widely applicable principle is that plant succession will be set back most and species composition will be most altered with the most intense fires. The time each listed species remains important in the plant community will be site specific, and probably cannot be extrapolated beyond the listed habitat types in western Montana, northern Idaho, and southern British Columbia, and then will apply only in series of years with weather similar to that experienced in 1967-1976.

Virtually the same guidelines apply to separability of the small mammal data to other forest types. The quantified population changes, species by species, will apply only to the same habitat types treated in a manner similar to that on Miller and Newman. Almost universally applicable, however, is the principle that clearcutting and fire removes the forest and causes marked declines in forest-dwelling species. This occurs with a concomitant increase in small mammals that inhabit early stages of plant succession. All levels of application between these two extremes are possible, being dependent upon the conditions with which the land manager is working.

Soils and watershed results are also dependent upon a combination of physical and biological processes. Immediate effects are largely physical—soil bared by logging and fire is subjected to overland flow and erosion, soil water repellency may be induced, and some plant nutrients will be volatilized in the fire. Effects manifested in the long term are largely driven by biological processes, such as recovery of vegetal cover on the soil, nutrient transport from the ash into the mineral soil and its later uptake by vegetation, and changes in organic matter content. The amount of soil bared is related to factors associated with fire effectiveness and can be predicted over a wide area. The amount of runoff and erosion to be experienced from a given amount of bare soil, however, will depend upon additional variables, such as slope, soil porosity and texture, and rainfall amounts and intensities. Hence, predictions of runoff and erosion are less widely applicable. The cited fertility changes will apply to similarly treated western conifer forests growing on well-drained soils of medium to fine texture; but the magnitude of these changes will vary from site to site.

Fire and smoke column from an evening prescribed fire in broadcast larch/fir slash.

RESULTS

This section is presented in six units, each written by the principal investigator(s) most closely associated with the specific data being discussed. These results are integrated and interpreted in the Discussion section that follows. The six units here are:

Fire Behavior and Effects—by Rodney A. Norum
Air Quality and Smoke Management—by D. F. Adams and others.
Silviculture—by Raymond C. Shearer
Vegetative Recovery and Development—by Peter F. Stickney
Small Mammal Populations—by Curtis H. Halvorson
Soils and Watershed—by Norbert V. DeByle and Paul E. Packer

Fire Behavior and Effects

Rodney A. Norum

Pacific Northwest Forest and Range Experiment Station
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The burning of forest fuels can vary tremendously, leaving widely different conditions afterward. As succeeding parts of this section will reveal, certain postfire conditions are important to the achievement of selected land management objectives. Perhaps most influential of all fire effects is the modification of the organic covering of the forest floor. The amount of duff consumed as well as the amount remaining each have a profound influence on vegetative response. The physical and chemical status of the soil is affected, along with watershed performance, and even the animal community may respond to differing degrees of duff removal. Therefore, one of the key objectives of the fire study was to determine the amount of duff removed and the amount retained when slash fires are burned under various conditions of fuel moisture and duff moisture, and with different amounts of fuel present. In addition, because of hazardous fire conditions represented by slash fuels, the amount of fuel consumed by fire over a range of fuel and atmospheric conditions was also measured.

Although the results of this study were reported by Beaufait and others (1977), results from subsequent fire research, combined with these, and a reanalysis of the pooled data have led to additional useful information. Applicable results from both Miller-Newman and later research and analyses are summarized here.

FUEL CONSUMPTION

Beaufait and others (1977) had difficulties statistically describing fuel consumption based on preburn measurements because treatments were biased by fuel loading values. Later research has not entirely relieved the problem, but a practical rule of thumb is now offered.

Small (<4-inch or <10-cm) diameter fuels are of paramount importance. They contribute most to the rate of spread on the fire front and to peak intensity. Consequently, they are most important to managers seeking fire hazard reduction. As discussed later, these fuels influence many important results of prescribed fires, such as duff reduction. Therefore an estimate of how much small fuel may be consumed in fires burning under selected and monitored conditions is necessary.

Experience on approximately 100 broadcast fires in larch/Douglas-fir forests, both on clearcuts and under standing timber, indicates that a safe and practical range of water contents is between 10 percent and 17 percent in the small diameter fuels. Below 10 percent water content the fire behavior and fire intensity becomes increasingly extreme, and control problems mount. Above 17 percent the fire becomes increasingly difficult to ignite and an effective fire treatment less likely. By pooling the data from Miller and Newman with subsequent data from fires burned within the 10 to 17 percent range, a simple but reliable estimate of reduction of fuels less than 4 inches (10 cm) diameter is possible with the linear regression equation:

$$Y = 0.78X$$

in which

Y = estimated reduction of small diameter fuels (kg/m^2)

X = preburn weight of small fuels (kg/m^2).

With the pooled data, this regression had a coefficient of determination (R^2) of 0.72.

For management, an obvious prescription criterion would be a water content between 10 percent and 17 percent in the small fuels. If burned within this range, approximately 78 percent of these fuels will be consumed. This is a safe and practical range of burning conditions that occurs frequently during late spring and early summer and again in late summer and early fall in the Northern Rocky Mountains.

Consumption of larger fuels (>4 inches or >10 cm in diameter) will vary from meager to nearly complete, depending on long-term drying conditions preceding the fire. Because of limited research results, no quantitative guidance for these fuels can be offered at this time.

DUFF CONSUMPTION

Duff depths and duff reduction measurements were taken on all fires as described by Beaufait and others (1977). They used upper duff moisture content and buildup index as independent variables in a regression equation to describe and predict duff depth reduction. Regression equations of duff weight on duff depth were derived in order to use the simpler depth measurements taken for fuel inventory purposes.

Subsequent to that report, the data from the Miller-Newman study were combined with identical data from 31 additional experimental fires in

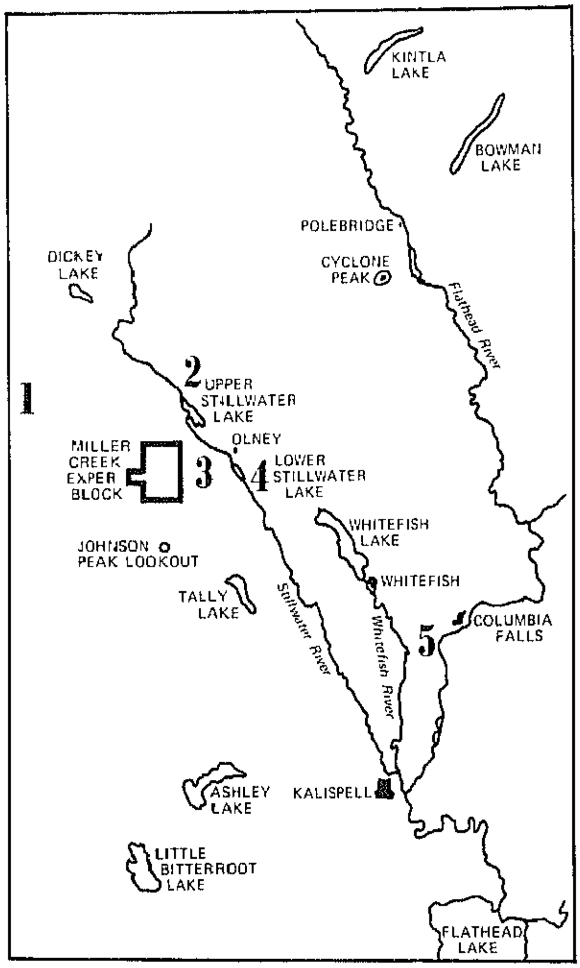


Figure 7.—Location of the five air quality stations at ground level in the vicinity of the Miller study area.

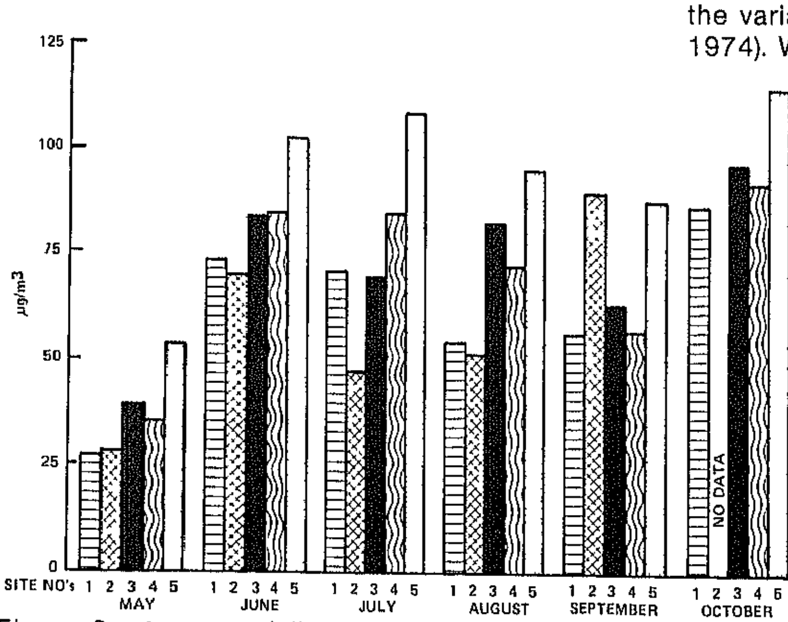


Figure 8.—Average daily suspended particulate concentration by months in 1968 at five air quality stations near Miller.

These data were analyzed by (a) all days with prescribed fires, (b) all weekdays with no fires, (c) all weekends, and (d) all days. Sites 3 and 4 have highly significant differences between fire days and all other day types (fig. 9); they are downwind from the prescribed fires. Sites 1 and 2, located west and north of the Miller block, did not have statistically significant differences by types of days. Site 5 also showed statistically significant differences between fire days and other weekdays. This site also had highly significant differences between nonfire weekdays and weekends, reflecting the influence of weekday commercial and industrial activities (such as tepee burners) in this valley. An analysis was run comparing the day after fires to all other nonfire days. They were statistically alike, indicating no holdover of particulate matter in the air from the previous day's fire.

Interestingly, there were higher average values on weekends at the four forest sites than on nonfire weekdays, probably due to dust from increased recreational traffic on forest roads and trails on weekends.

AIRCRAFT MONITORING OF SMOKE AND EMISSIONS

The height attained by the smoke columns from 22 of the Miller fires was measured. A regression analysis showed that relative fire intensity, water content of the upper half of the duff layer, windspeed at 20 feet (6.1 m) above ground (local surface windspeed), and atmospheric mixing depth at time of burning explained 80 percent of the variability in smoke column heights (Norum 1974). Within the range of atmospheric stability

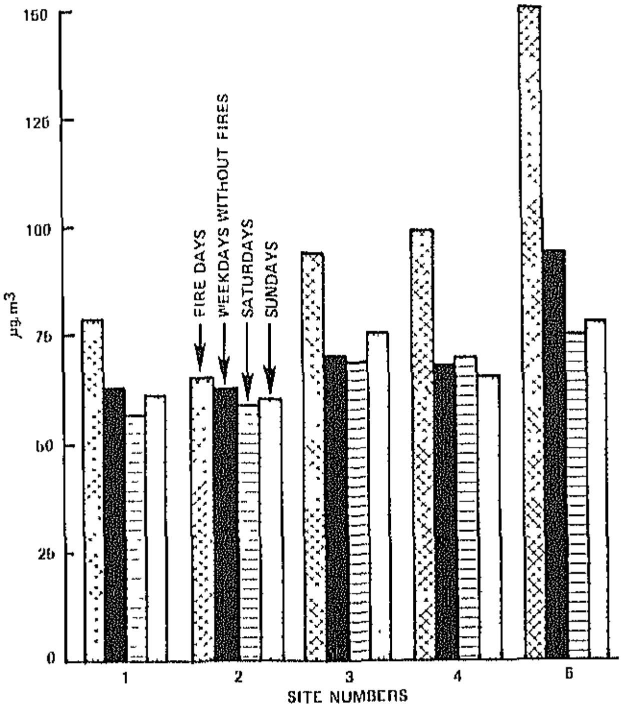


Figure 9.—Mean concentration of suspended particulates for fire days, other weekdays, and weekends from June to October 1968 at the five stations near Miller.

conditions under which these fires were conducted, those variables most closely associated with fire intensity (wind and fuel dryness) and a measure of fire intensity itself (evaporation from water can analogs [Beaufait 1966a]) were more influential than mixing depth in controlling the height of smoke rise. Norum (1974) concluded that atmospheric stability alone is inadequate for describing level of smoke rise from high-intensity 10-acre (4-ha) broadcast slash fires.

The smoke plumes were tracked with the airborne nephelometer more than 30 miles (approximately 50 km) downwind from several fires. Particulate matter in the downwind plumes from the Miller fires ranged from 90 to 230 $\mu g/m^3$; average background loading at that elevation was 18 $\mu g/m^3$. At the same time, carbon dioxide (CO_2) levels approximately 10 percent above background levels were found in the plumes nearly 16 miles (25 km) from their source. As the plumes grew and developed, there was a simultaneous increase in CO_2 concentration and particulate matter concentration that could be detected up to several miles downwind. The fact that CO_2 peaks coincide with visible plume and particulate peaks indicates that a large portion of the solid particulate matter is in a size class that moves essentially as a gas.

Energy from the relatively intense fires monitored by the aircraft pushed smoke plumes well above the mixing depth. Plumes from some intense fires at Miller rose up to 8,000 feet (2 440 m) higher than the mixing depth. As a result, even when the combustion products drifted south and over the populated valley, the plume was at least 3,300 feet (1 000 m) above the polluted valley air, and the plume could readily be tracked further downwind without confusion. On the other hand, less intense fires produced smoke columns that rose only to the mixing depth. Such fires may pollute the valley air, especially if they smolder into and through the night. This type of fire may have contributed to increased particulate matter levels at Station 5 on fire days. Of course, fallout of larger particulates downwind from intense fires would account for much of the increases at Stations 3, 4, and 5 on fire days, too.

Smoke plumes from the combined burning of units S-4 and S-10, and from the separate burning of E-10 and E-14 on Miller were closely monitored. The combined S-4 and S-10 plume rose to 14,400 feet (4 400 m) at a rate of 5 ft/s (1.5 m/s). Approximately 455 tons (413 t) of fuel were consumed. The columns from E-10 and E-14 rose to 11,500 feet m.s.l. elevation (3 500 m) at rates of 4.3 and 6.6 ft/s (1.3 and 2.0 m/s), respectively. The fuel consumed, exclusive of the duff, was approximately 132 and 176 tons (120 and 160 t), respectively. The greater energy release from the larger quantity of fuel on E-14 may have caused the greater rate of column rise, as both of these were burned the same evening under similar atmospheric conditions. Also, both ambient air temperature and height of free air convection were greater during the S-4 and S-10 fires, additional causes for the column from this fire to rise almost 4,000 feet (1 200 m) higher than the columns from the fires on E-10 and E-14.

The prescribed slash fires produced rapidly changing conditions for generation and rise of combustion products. Usually there was a rapid rise in the rate of energy release that resulted in rapid plume development and a boost of that plume to relatively high elevations. Then, after burning intensely, as illustrated on the cover photo, for, say, an hour, the available fuels were consumed and the fire quickly died down. The convection column rose from 4 to 7 ft/s (1.3-2.0 m/s) during this rapid rise in energy release rates. After reaching their ultimate height, the smoke plumes tended to concentrate at the level of greatest windspeed. There they moved with the wind as gradually widening rivers of smoke of limited depth. Aircraft monitoring of lateral smoke

dispersion showed that the expected dispersion from a point source, a smoke stack, applies equally as well to dispersion of these smoke plumes (Adams and others 1976). The particulates in this smoke, for the most part, remain aloft as aerosols embedded in the air layer into which they were initially lifted. Most of these particulates ultimately would become condensation nuclei in precipitation and return to the earth's surface.

A number of nephelometer readings were used to construct a composite vertical profile of visibility on July 11, 1969, during a time when smoke was being transported into western Montana from fires hundreds of miles away. Visibility was restricted to approximately 5.6 miles (9 km) between 8,000 and 12,000 feet (2 440-3 660 m) elevation above m.s.l. but increased to approximately 9.3 miles (15 km) in the layers both above and below. This illustrates the point that smoke is advected into stratified layers in the atmosphere and remains there while moving along with wind currents.

Measurements of local winds aloft are essential to develop a reliable forecast, especially for plume behavior and dispersal. This need is pointed out with the data from aircraft monitoring of plumes from Miller fires S-4 and S-10 on July 3, 1968 (fig. 10). Speed of plume travel and the difference between ground and airspeed of the plane indicated an average wind of 40 mi/h (18 m/s) between 7,100 feet and 12,950 feet m.s.l. (2160-3950 m) at the study area. In contrast, RAWINSONDE measurements at the nearest station having this capability (Spokane, Wash., some 242 miles [390 km] away) showed windspeeds of only 13 mi/h (6 m/s) at that altitude. The direction at Spokane correlated well with the measured trajectory of the smoke column, but the windspeed was only 35 percent of that over the study area.

Peak concentrations of particulate matter near 1650 $\mu g/m^3$ were observed in the smoke plumes from the Newman fires in 1969. This may be an upper limit to smoke concentrations in an atmosphere with neutral temperature lapse conditions at distances up to 6 miles (10 km) downwind from the source. Concentrations of this magnitude are considered hazardous to health (U.S. Department of Health, Education, and Welfare 1969), reduce visibility to approximately one-half mile (800 m), and are an aircraft navigation hazard.

Several monitored plumes had a forked pattern similar to the plume from Miller S-4 and S-10 shown in figure 10. It is speculated that the combined forces of directional shear in the vertical and irregular energy release rates by the fire both contributed to this pattern.

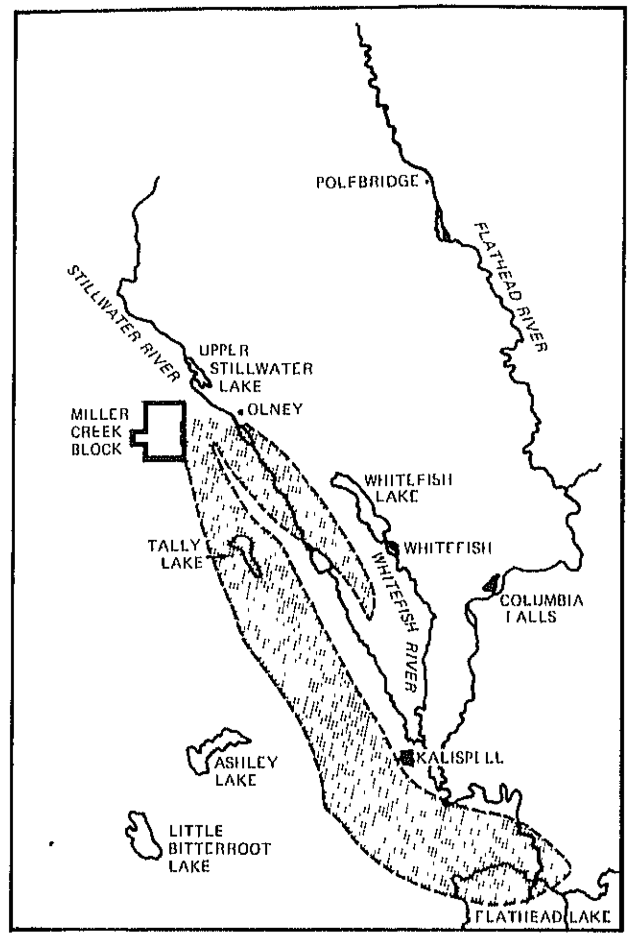


Figure 10.—Map of the maximum monitored spread and configuration of the smoke plume at 13,000 feet above MSL from the slash fire on units S-4 and S-10 at Miller on July 3, 1968.

SMOKE COMPOSITION

The largest components of forest fire smoke are carbon dioxide, water, and particulate matter. As already noted, particulates and carbon dioxide were detected above background levels in the plumes from the prescribed fires at Miller and Newman. The particulates may be organic or inorganic and are usually composed of carbon or mineral ash. The amounts of particulate matter and some gaseous emissions from inefficient fires are greater than those from efficient fires. The differences are roughly proportional to combustion rates. A fire that burns intensely may produce only a tenth as much particulate matter and unburned byproducts as one that burns slowly, spanning day and night and over a range of burning conditions (Beaufait 1971).

The fuel weights before and after burning the experimental units were sampled in detail. On the average, 60 percent of the fuels were consumed.

These fuel inventories, chemical analyses of the fuels, and analyses of combustion products from burning small quantities of these fuels in the laboratory were used in conjunction with the limited analyses of components in a few prescribed fire plumes to estimate the emission products from these fires.

Malte (1975) examined the results from three Newman fires (N-1, S-2, and W-2) in detail. He calculated ratios of particulate density to CO_2 density, usually finding a correlation (figs. 11 and 12). The particulates and CO_2 moved more or less together in the plume. Fire S-2 (fig. 11) clearly showed an increase in particulate matter (visible smoke) relative to CO_2 with time, whereas fire W-2 (fig. 12), burning more rapidly, had a peak ratio about 60 minutes after ignition.

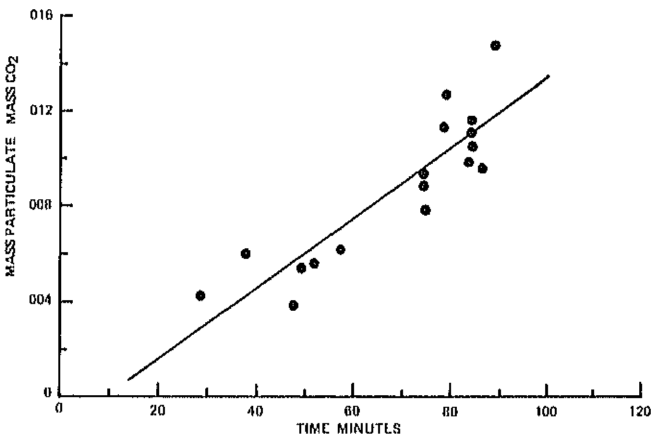


Figure 11.—Ratio of particulate concentration to carbon dioxide concentration in smoke plume from unit S-2 at Newman.

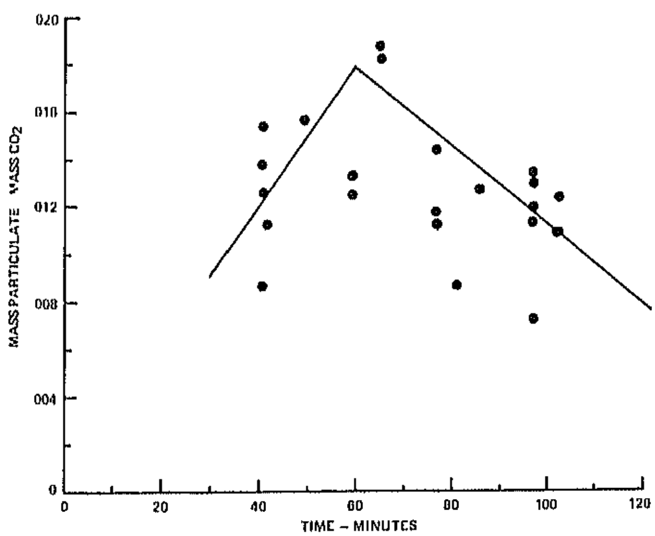


Figure 12.—Ratio of particulate concentration to carbon dioxide concentration in smoke plume from unit W-2 at Newman.

Figures 13 and 14 illustrate the concentrations of particulate matter and carbon dioxide, respectively, in the plume from fire S-2. Straight lines are drawn through data obtained at similar downwind positions, for example, at relative position "2". Of the three fires, this one best shows the increase in both CO_2 and particulate matter in the plume as the fire developed and grew Concentrations in fire S-2 were only about half as great as in W-2 and the rates of increase were much lower, indicating that fire W-2 was the more intense of the two and burned at a faster rate. For fire N-1 the trend of increasing particulates with increasing time is similar to that observed in S-2 and W-2, with the values being about the same as for S-2. However, such weak CO_2 signatures were obtained from N-1 that its concentration in the plume could not be distinguished from background.

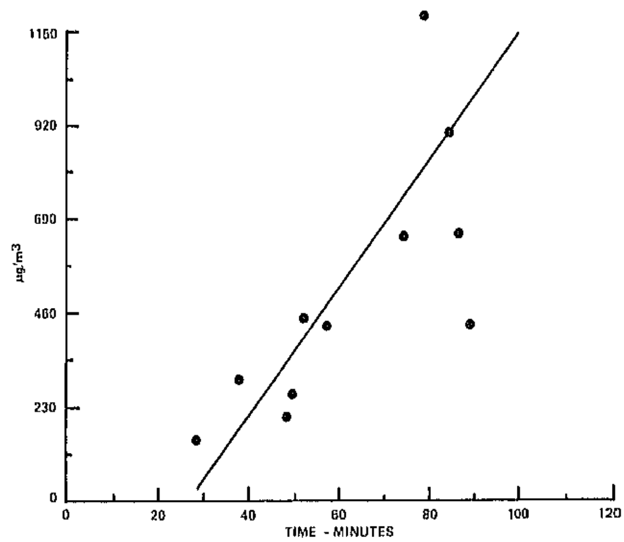


Figure 13.—Particulate concentration over time in the smoke plume from unit S-2 at Newman.

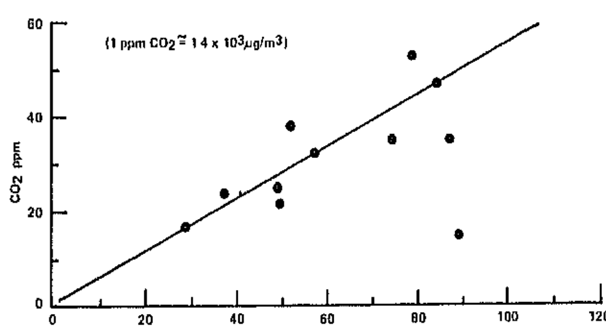


Figure 14.—Carbon dioxide concentration in the smoke plume from unit S-2 at Newman.

Generally, the ratio of particulate matter to CO_2 will vary with time and with position in the plume due to phenomena that are fluid dynamic or chemical in nature. As the fire grows, the intensity of convective currents increases, and particulates will be carried more readily by the plume gases. As downwind location is increased, less particulate matter is expected because of relatively rapid upwind fallout of the coarse particulates, those that are larger than aerosols. The nature and efficiency of combustion processes affect the formation of smoke and, thus, the ratio of particulate to CO_2. As the different slash fuel sizes and types undergo drying, pyrolysis, gasification, and surface oxidation, the nature of the overall fire and its smoke production change. In these fires it was found that an increase in the water content of fuels led to a reduction in the amount of carbon dioxide produced per unit of burned slash.

Chemical analyses of the fuels by category (duff, needles and twigs, and material larger than 4 inches [10 cm] in diameter) and of their combustion products were carried out in the laboratory. Duff and its residue after burning, for example, were found to contain the following elements in percentage of total ovendry weight:

	Duff	**Burned residue**
	Percent	
Carbon	37.3	8.6
Hydrogen	3.3	0.4
Nitrogen	1.5	0.4
Oxygen	15.4	0.9

Burning increased the ash content to 89.7 percent. This duff, burned when dry, gave a CO_2 ratio of 0.885; the remainder (0.115) was assumed to be carbon monoxide (CO).

Without going into the details of the stoichiometric procedures followed, as they are covered by Malte (1975), the following formulas were developed to calculate the total amounts of carbon dioxide (formula 1), carbon monoxide (formula 2), and nitrogen dioxide (formula 3) produced from the different fuels in a slash fire:

$$\begin{aligned} \text{kg } CO_2 = {} & 2.08\, Y_M \left(\frac{W_i}{1+M} - W_f\right)_{\text{duff}} \\ & + 1.66\, Y_M \left(\frac{W_i}{1+M} - W_f\right)_{\text{needles and twigs}} \\ & + 1.76\, Y_M \left(\frac{W_i}{1+M} - W_f\right)_{\text{branches and logs}} \qquad (1) \end{aligned}$$

$$\begin{aligned} \text{kg } CO = {} & 4.63\, (1.038\, Y_M) \left(\frac{W_i}{1+M} - W_f\right)_{\text{duff}} \\ & + 1.05\, (1.038\, Y_M) \left(\frac{W_i}{1+M} - W_f\right)_{\text{needles and twigs}} \\ & + 1.13\, (1.038\, Y_M) \left(\frac{W_i}{1+M} - W_f\right)_{\text{branches and logs}} \qquad (2) \end{aligned}$$

$$\begin{aligned} \text{kg } NO_2 = {} & 0.08 \left(\frac{W_i}{1+M} - W_f\right)_{\text{duff}} \\ & + 0.034 \left(\frac{W_i}{1+M} - W_f\right)_{\text{needles}} \qquad (3) \end{aligned}$$

In these formulas the terms are defined as:

Y_M = moles CO_2/moles total carbon as determined from the relationship with water content of fuel. Ratio is 1.000 with no water, decreases 0.022 with each 10 percent increase in water content, and, thus, is 0.890 at 50 percent fuel water content.

W_i, W_f = initial and final (residue) masses of individual slash fuels, including moisture content of initial fuel.

M = water content as decimal fraction for individual slash fuels.

Potentially, most of the NO_2 would have come from the burned duff (it contained 1.5 percent N) and needles (they contained about 1.0 percent N) in the total fuel bed because the woody twigs and larger fuel components had less than 0.05 percent N content. Hence, formula 3 includes only duff and needle categories.

The emission of CO_2, particulate matter, CO, and NO_2 per unit of consumed fuel are presented and discussed for the Newman fires. To do this, formulas 1, 2, and 3 were used together with fuel water contents and pre-and postburn inventories for these units. The water contents for the different fuel components on these units are presented in table 3. The ranking of fires from wet to dry is: S-2, average of all eight Newman fires, N-1, and W-2.

Table 3.—Water content of Newman fuels

Unit	Duff[1]	Needles[2]	Diameters of woody fuels		
			[2]0-1 cm	[2]1-10 cm	[3]10+ cm
	Percentage of ovendry weight				
N-1	35.5	6.2	10.0	11.1	12.2
S-2	53.2	5.4	8.1	22 0	35 9
W-2	29.8	5.5	8 6	11.1	13.6
Average of 8 units	37.5	8 2	10 2	13 7	17 2

[1]Average of upper and lower duff

[2]Average of upper one-fourth and lower one-fourth of fuel bed

[3]Extrapolation, assuming same difference between moisture content for 10+ cm material and 1-10 cm twigs as between moisture content for 1-10 cm twigs and 0-1 cm twigs.

Table 4.—Fuel inventory of selected Newman units

Unit and conditions	Duff	Needles	Branches and stems			Total
			0-1 cm	1-10 cm	>10 cm	
	kg/m²					
N-1						
Before	109.8	4 00	2 92	19.2	247 8	383.7
After	53.1	03	.02	2 9	139.4	195.4
Burned	56.7	3.97	2 90	16.3	108.4	188.3
Percent burned	*52*	*99*	*99*	*85*	*44*	*49*
S-2						
Before	106.0	2 54	2.54	25.9	213.8	350 8
After	56.5	58	58	4.2	57 0	118 8
Burned	49.5	1.96	1.96	21 7	156 8	232 0
Percent burned	*47*	*77*	*77*	*84*	*74*	*66*
W-2						
Before	106.6	2.48	2.07	23.4	237.0	371.6
After	60.7	.04	.03	2.1	86.0	148 9
Burned	45.9	2 44	2.04	21 3	151.0	222 7
Percent burned	*43*	*98*	*99*	*91*	*64*	*60*
Average of 8 units						
Before	110.9	3.5	2.56	27.1	209 5	353.6
After	63.4	0	.20	3.3	93.5	160.4
Burned	47.5	3.5	2.36	23.8	116.0	193.2
Percent burned	*42*	*100*	*92*	*88*	*55*	*55*

Fuel inventories for these Newman units are presented in table 4. Slightly over half of the total fuel consumed was larger than 4 inches (10 cm) in diameter. Duff represented about a fourth of the burned fuel, twigs one-third to 4 inches (1-10 cm) diameter comprised a tenth, and small twigs and needles contributed equally to the remainder.

Table 5, the mass of gases and particulates produced per mass of total fuel burned, is derived from the above formulas and tables 3 and 4. The particulate emission index was determined by multiplying the CO_2 emission index by the mass ratio of particulate matter to CO_2, which was determined from aircraft measurements of the smoke plume. A value is given only for W-2 since this was the single case for which plume data were sufficient to estimate the particulate/CO_2 ratio. A value for NO_2 is given only for the average of the eight Newman fires. At most, only 1 percent of the total slash fuel could form NO_2.

Generally, needles and small twigs gave negligible (<3 percent) contributions, except for NO_2, because of the small quantities present. The duff and larger twigs and branches (1-10 cm) each contributed slightly more than 10 percent of the CO_2; but the primary contribution to CO_2 was material larger than 10 cm in diameter. For CO the situation was somewhat different—duff and material >10 cm were the major CO sources, each contributing about equal amounts.

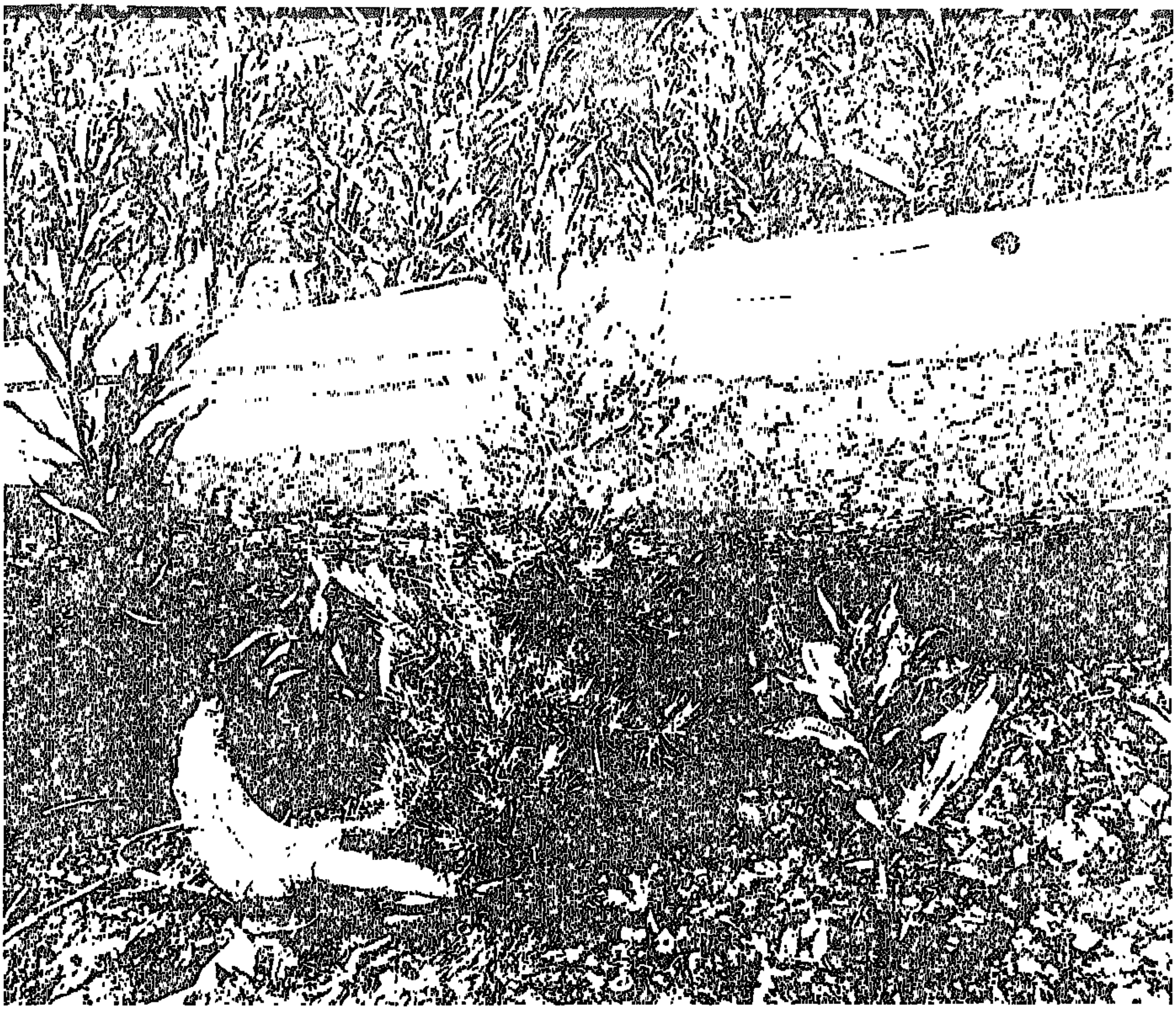
The mass of CO emitted per mass of burned fuel was essentially constant in all fires, having a value about 0.13. However, the mass of CO_2 emitted increased with decreasing water contents of the fuel. The ranking of the fires from low to high CO_2 formation is identical to the ranking of fuels from wet to dry. Note also that the concentrations of CO_2 in the plumes of fires S-2 and W-2 illustrate dependence on fuel water content; the CO_2 concentration in the plume from the dry fuels on W-2 was about twice as great as from the wetter fuels on S-2. Apparently the conversion of fuel carbon to CO_2, rather than CO, was enhanced by more efficient combustion of the dry fuels.

The amount of particulate matter produced per unit of fuel burned should be of concern to the manager. Calculations of this parameter, using different portions of these air quality data, gave results from approximately 10 lb of smoke particulate per ton of fuel burned (burning table date), to 33 lb per ton (using factor 0.016 in table 5), to 48 lb per ton (Miller smoke plume data). Though more reliable data would be desirable, a reasonable estimate from these data is approximately 30 lb of particulate matter produced in the smoke from each ton of fuel (15 kg/t) consumed in these fires.

Table 5.—Mass of CO_2, CO, particulates, and NO_2 per mass of total slash[1] burned on selected Newman units

Unit and component	Source of contribution					
	Duff	Needles	Branches and stems			Total
			0-1 cm	1-10 cm	>10 cm	
N-1						
CO_2	0 248	0.033	0.023	0.124	0.740	1.168
CO	.080	.001	001	.005	.033	.120
S-1						
CO_2	.100	.013	.012	.116	.703	.944
CO	.038	.001	.001	.007	.093	.140
W-2						
CO_2	.235	.022	.017	.173	1.179	1.626
CO	.058	.001	.001	.007	.055	.122
Particulates	—	—	—	—	—	.016
Average of 8 units						
CO_2	.169	.027	.018	.170	.745	1.129
CO	.050	.001	.001	.013	.065	.130
NO_2	.007	.001	—	—	—	.008

[1]Including water content of slash.



Western larch seedling developing in the protection of a charred log on Miller unit W-1 6 years after broadcast burning.

Silviculture

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The interaction of seedbed condition, seed availability, and environmental factors restricts conifer regeneration following prescribed fires. Any of these alone may limit regeneration to unacceptably low levels. For example, mineral soil may not be exposed, no seeds may mature, or animal populations, insolation, or drought may cause excessive seedling mortality.

The conditions following prescribed fires in clearcuts at Miller and Newman are described and related to conifer regeneration. These results are contrasted with nearby uncut areas burned by wildfire or slashed but unburned clearcuts.

SEEDBED CONDITION

Prescribed fires from May through October on all cardinal exposures produced a wide range of seedbed conditions. Duff reduction was limited by duff water content. When the lower half of the duff was below 50 percent ovendry weight, almost all duff was burned. However, when the water content of the lower half of the duff was above 100 percent, usually less than half burned. Reduction in duff thickness ranged from 11 to 100 percent at Miller and from 65 to 90 percent at Newman.

Prescribed fires in logging slash caused only minor changes in soil water content and soil heating except during fires of high intensity, when the initial water content of both soil and duff was low. When the water content of soil and duff was high, fires caused no change in content of soil water and only a slight change in duff water As duff dried, the prescribed fires burned a greater proportion of the duff layer, which, in turn, caused more water loss from and heating of the surface soil. When both fuels and upper soil had low moisture contents, water loss and heating occurred as deep as 4 inches (10 cm) into the soil. Soil heating associated with prescribed fires decreased rapidly below the soil surface (table 6). Maximum temperatures within the upper 1.6 inches (4 cm) usually were reached between 1 and 2 hours after ignition.

Table 6.—Maximum temperatures reached within the soil under three percentages of duff reduction[1]

Depth in soil	Percent duff reduction 23	61	82
Inches (cm)	F(C)		
0	142 (61)	234 (112)	320 (160)
0.4 (1)	125 (52)	163 (73)	196 (91)
1 2 (3)	<113 (45)	120 (49)	124 (51)
2 0 (5)	<113 (45)	<113 (45)	<113 (45)

[1]Adapted from Shearer (1976), p. 488-489

During prescribed fires, significantly greater duff reduction and heating of the mineral soil surface took place at Newman than at Miller. Three-fourths of the sample points reached maximum temperatures between 200°F (93°C) and 400°F (204°C) at Newman but, at Miller, three-fourths reached only 138°F (59°C) to 163°F (73°C). Greater surface soil heating occurred at Newman because of a shallower duff layer and lower water contents of both fuel and soil than at Miller. Average duff reduction varied at Newman from 44 percent at 113°F (45°C) maximum surface soil temperature to 99 percent at 500°F (260°C); at Miller from 36 percent at 125°F (52°C) to 70 percent at 400°F (204°C).

Heat-caused mortality of nonconiferous roots or rhizomes varied according to soil water content and depth and degree of soil heating. Spring fires of any intensity caused root mortality only in the upper 0.4 inch (1 cm) of soil. Low-intensity fires over dry soils caused considerable root mortality in the surface 2 inches (5 cm) but relatively little below that level. Only the combination of high-intensity fire over dry soils killed most roots in the upper 4 inches (10 cm).

SEED PRODUCTION AND DISPERSAL

Good seed crops occur infrequently. At both study sites from 1969 through 1974, the only good seed crop was produced in 1971. Poor crops were produced in 1970 and 1974, and failures occurred in 1969, 1972, and 1973. At Miller a fair crop was produced in 1967 and a poor one in 1968. Most natural regeneration reported for both areas originated from the good 1971 seed crop. The fair 1967 crop partially regenerated cutover Miller units burned that year. In addition, three units of uncut trees, most of which were killed by a wildfire in late August 1967, disseminated considerable seed from fire scorched cones.

In 1971 the residual timber produced an average of 51,000 and 34,000 sound seeds per acre (126000 and 84000 per hectare) at Miller and Newman, respectively. The number of seeds produced by each species varied widely, usually reflecting stand composition. Although variability is great from unit to unit, an average of 37,000 sound seeds per acre (91 400/ha) fell into the 10-acre (4-ha) clearcuts at Miller, and an average of 10,000 per acre (24700/ha) fell into the much larger clearcuts at Newman. This represents only 29 and 12 percent, respectively, of the seedfall in the surrounding forest. A higher percentage of seed fell in clearcuts at Miller becuase the openings were smaller than at Newman.

The distribution of sound seed at Newman decreased sharply from the timber edge to about 300 ft (90 m) into the clearcut openings, then continued at a low but uniform rate up to about 800 ft (244 m) from the timber (table 7). The average number of sound seed per acre declined from 42,900 in the belt 0-200 ft from the timber edge to 11,500 in the belt 600-800 ft from the timber (106 000/ha in 0-61 m belt to 28 400/ha in 183-244 m belt). Seedfall was greatest within south-facing clearcuts; this was followed in order by west-, east-, and north-facing clearcuts. During the prime seedfall hours of noon to 6:00 p.m., when air temperature is highest and relative humidity lowest, average wind velocities were much higher on south- than on north-facing slopes. Velocities ranged from 3.5 to 5 mi/h (5.6-8 km/h) greater on south- than north-facing slopes during the primary hours seed is dispersed.

ıle 7.—Cumulative number of sound seed per acre (hectare) dispersed from 1969 through 1974 on eight clearcut units on Newman by distance from seed source

cies	Within timber	Distance from timber edge within clearcut			
		0-200 ft (0-61 m)	200-400 ft (61-122 m)	400-600 ft (122-183 m)	600-800 ft (183-244 m)
	Hundreds per acre (hectare)				
las-fir	1,228 (3 033)	217 (536)	103 (254)	42 (105)	84 (208)
ərn larch	532 (1 315)	75 (186)	37 (92)	20 (49)	8 (19)
əıosa pine	276 (681)	21 (53)	12 (29)	6 (14)	0 (0)
ı fir	241 (596)	69 (170)	19 (48)	23 (56)	15 (38)
əpole pine	22 (54)	11 (26)	3 (6)	0 (0)	0 (0)
mann spruce	30 (75)	30 (74)	8 (19)	3 (7)	8 (19)
	11 (26)	6 (16)	3 (6)	6 (14)	0 (0)
	2,339 (5 780)	429 (1 060)	184 (455)	100 (247)	115 (284)

rcentage of sound seed in the good 1971 ɔp at Newman was about three times ıan the average of the other five poor or ops as shown:

	Western larch	Douglas-fir	Engelmann spruce
971)	16	43	48
ı '1)	15	39	45
ı ıer years)	4	11	18

NATION

/ere sown so germination and the effects nmental factors on tree seedling surviv- be effectively measured. Initial seed ger- varied by species, from several days ıowmelt (western larch) to about 3 weeks ıgelmann spruce). Douglas-fir, grand fir, sa pine, and lodgepole pine seeds began ing soon after snowmelt. Germination peaked the week following snowmelt, lined steadily, and ended within a month, exception of spruce. Some spruce seed d to germinate throughout the summer ır the surface soil was moist.

ɔermination occurred on soil bared by arification than occurred on soil remain- a residual duff layer more than 0.5 inch thick. Germination differences between bare and duff-covered seedbeds were greatest on south- and least on north-facing slopes. However, more germination occurred on north- and east-facing slopes than on south- or west-facing slopes.

SEEDLING SURVIVAL

Several factors strongly influenced initial seedling survival. Severe seedling losses were caused by bird and rodent predation, by fungi, and by drought.

In the spring of 1968, migrating juncos killed over 90 percent of the newly germinated seedlings at Miller by clipping the cotyledons and removing seedcoats. After the seedcoats were shed naturally, these losses immediately dropped to a low but constant rate for the remainder of the summer.

Fungi caused considerable mortality of new seedlings until the surface soil dried, usually in mid- to late-June. These losses were greater on surfaces with scorched duff than on those burned to bare mineral soil. Fungi were the primary cause of seedling mortality at Newman on all but south-facing slopes.

Drought in late summer of most years caused extensive seedling losses. It was the leading cause of seedling death on south-facing slopes,

and the second most important on all other aspects. Most losses occurred in August, except in 1968, when rainfall saturated the surface soil during this period.

Frost heaving caused mortality of germinating seed and seedlings during their first autumn and spring. In early spring, germinating seeds and the surface layer of soil were lifted by and suspended on ice crystals. When the ice melted, the seeds and young seedlings dried. Year-old seedlings also were killed when frost heaved because the roots were broken or exposed.

Despite partial shading from microrelief, charred logs, and stumps, surface soil temperatures reached as high as 175°F (79°C) on unprotected east-, south-, and west-facing clearcuts from mid-June through early August. These high surface temperatures no longer occurred after vegetal cover developed and provided more continuous shade. Most seedling losses occurred in July. Seedlings growing on north-facing slopes, where the maximum recorded was 131°F (55°C), were nearly unaffected. Due to direct solar radiation, soil temperatures 20 inches (50 cm) below the surface on burned areas were 5° to 14°F (3°-8°C) higher than in the adjacent forest.

NATURAL REGENERATION

Natural regeneration on burned seedbeds was most successful on north-facing slopes and least successful on south-facing slopes. Even small changes in aspect affected survival. For example, on a Newman unit that included slopes facing 96°, 110°, and 141° azimuth, the number of seedlings per acre in 1973 on these exposures, respectively, were 1,401, 865, and 516, and the proportions of milacre plots stocked were 50, 45, and 32 percent.

In August 1967 at Miller a wildfire swept through several uncut stands on east-, south-, and west-facing slopes and killed most trees. However, many of those trees dispersed seed that autumn from their charred cones. Shade from the dead trees moderated site conditions enough to increase seedling survival, particularly on south-facing slopes (table 8). The shaded south-facing slope had 11 times more seedlings than adjacent clearcuts; the shaded east- and west-facing slopes had about three times more seedlings than bordering clearcuts.

In contrast to the burned areas, very little natural regeneration survived on unburned seedbeds. On north-facing unburned slopes at Miller there were only 200 seedlings per acre (494 per ha) and only 17 percent of the milacre plots were stocked. Unburned south-facing seedbeds had a mere 33 seedlings per acre (82 per ha), with a 3 percent stocking. Most seedlings growing under these conditions had poorer vigor and height growth than those growing on burned areas.

The number of filled seeds required to establish a seedling varied by habitat type and by the interaction of aspect and seedbed condition (table 9). At Newman the average seed/seedling ratio for all habitat types was inversely related to initial root elongation and to seed weight. That is, species with heavy seed and rapid initial rooting had low ratios while light seed and slow initial rooting had high ratios (table 10).

Table 8.—Seedlings per acre (hectare) and stocking of milacre plots under burned standing timber versus that on adjacent burned clearcuts at Miller in 1974

Aspect	Burned uncut forest		Clearcut and burned	
	Seedlings	Stocking	Seedlings	Stocking
	Number	*Percent*	*Number*	*Percent*
East	2,467 (6 096)	87	895 (2 212)	47
South	1,588 (3 924)	63	141 (348)	15
West	5,454 (13 477)	92	1,726 (4 265)	76

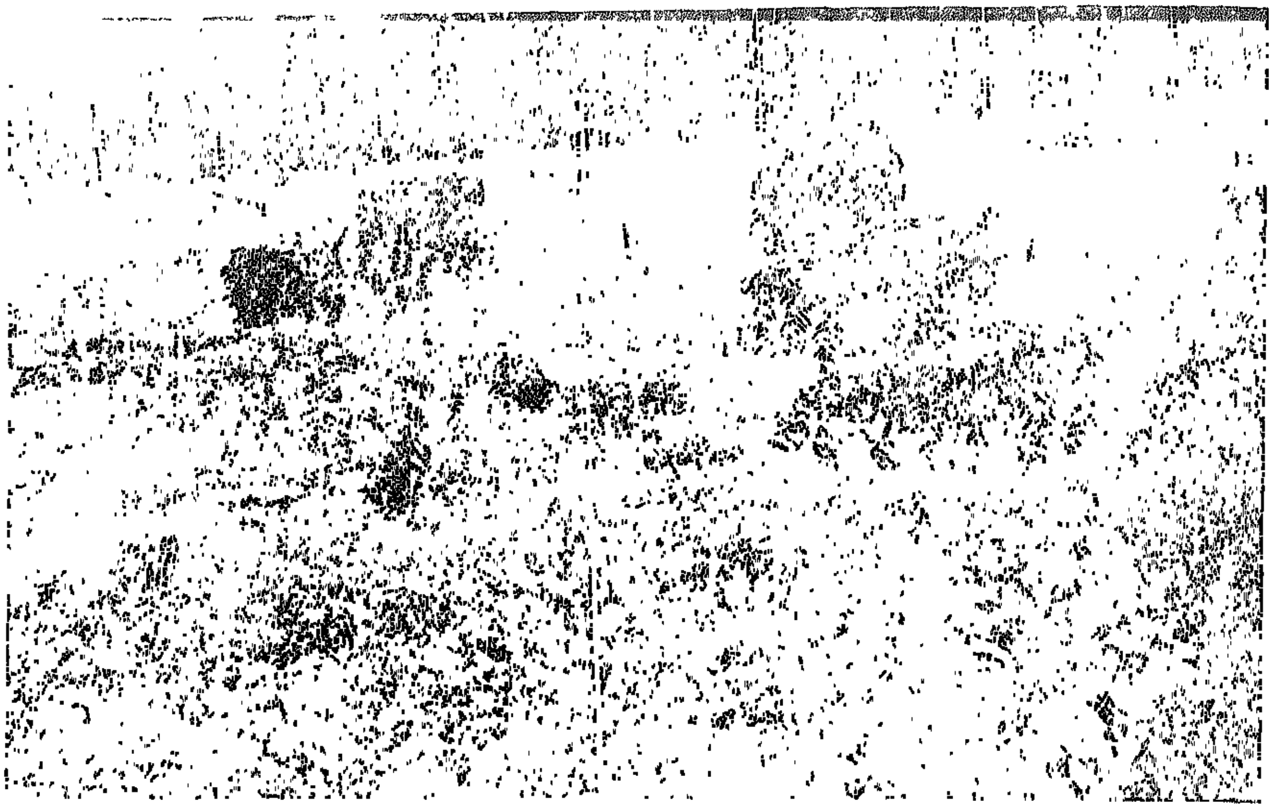
Table 9.—Average number of seeds required to establish one seedling at Miller and Newman by habitat type (Pfister and others 1977) and aspect—seedbed condition (Shearer 1976)

Habitat type	Aspect—seedbed condition	Seeds per seedling
Miller:		
Abies lasiocarpa/Clintonia (*Menziesia* phase)	Upper north and east—burned to mineral soil	17
Abies lasiocarpa/Clintonia (*Clintonia* phase)	Lower north, east, and west—burned to mineral soil	67
Newman:		
Thuja/Clintonia (*Menziesia* phase)	North—burned to mineral soil	6
Abies grandis/Clintonia	Northeast to east—burned to mineral soil	17
Abies grandis/Xerophyllum	East and southeast—burned to mineral soil	92
Abies grandis/Xerophyllum	West—burned to mineral soil	149
Pseudotsuga/Vaccinium globulare (*Xerophyllum* phase)	South—burned to mineral soil	185
Pseudotsuga/Vaccinium globulare (*Xerophyllum* phase)	South—rapid revegetation	659
Pseudotsuga/Vaccinium globulare (*Xerophyllum* phase)	West—scorched duff layer	668

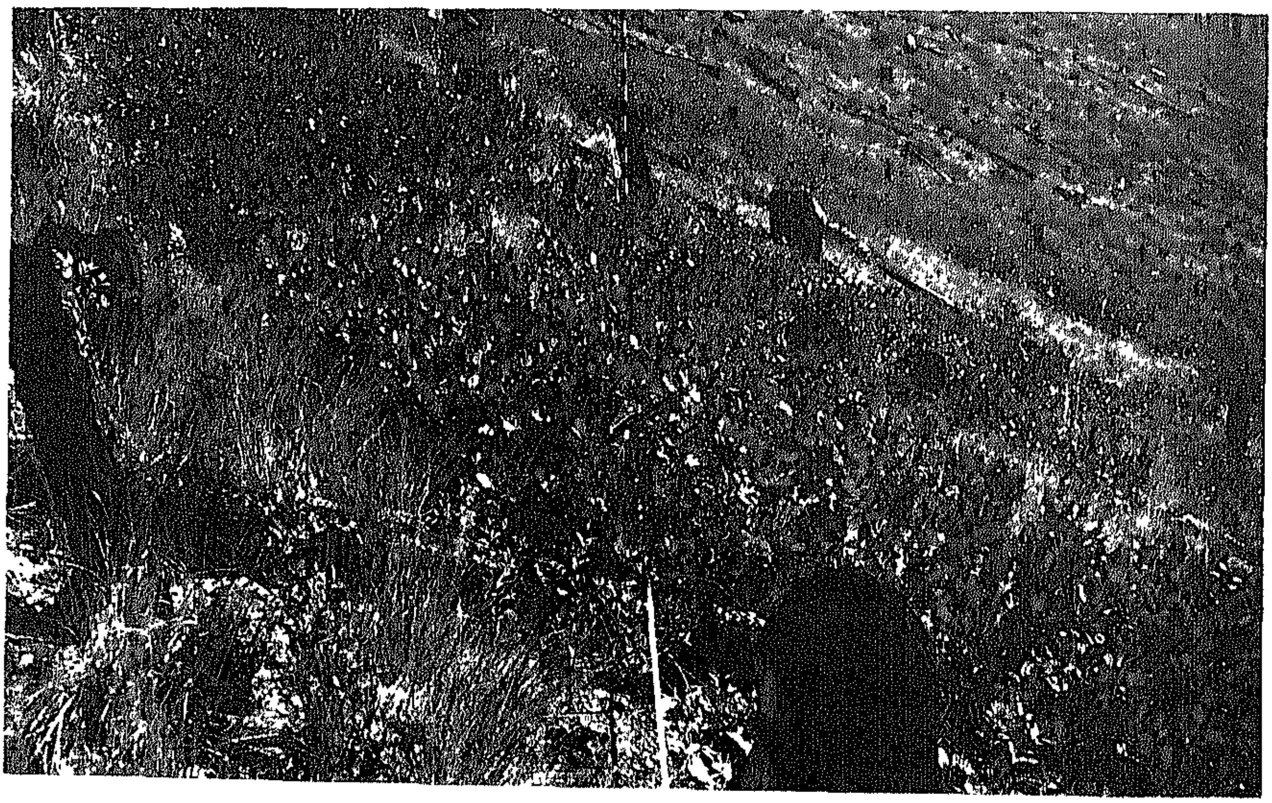
Table 10.—Seed weights related to seeds required at Newman to establish one seedling

Species	Seeds per pound[1]	Seeds per seedling
Ponderosa pine	12,000	11
Grand fir	18,400	16
Douglas-fir	44,300	44
Western larch	137,000	53
Engelmann spruce	135,000	74

[1]From U.S. Dep. Agric., Agric. Handb. 450, 1974. Washington, D.C.



Vegetation development on a larch-fir forest site (Miller unit E-9) 5 years after clearcutting and broadcast burning represents a well developed herb stage in forest succession.



Newman unit S-3, in 6 years of successional development following clearcutting and broadcast burning, has passed through a 3-year herb stage to the shrub stage of forest succession.

Vegetative Recovery and Development

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During the first 6 to 9 years after burning, development of vegetation on the 20 units studied at Miller and Newman followed a pattern characteristic for forest succession in the Northern Rocky Mountains This pattern is initiated by an herb stage, which is followed in turn by shrub and tree stages. In these few years, tree development was nonexistent or quite limited on most areas. Nowhere did trees attain community dominance. Using cover (crown area) of the predominant life form as the criterion for defining the successional stage, we find 9 of the 20 units had progressed to the shrub stage. All others remained in the herb stage.

HERB SUCCESSIONAL STAGE

The duration of the herb stage varied from 3 to 7 years on the 9 units that had progressed to the shrub stage. Seral vegetation that developed in the first postfire year originated from both surviving and newly established plants. This development varied widely in coverage, from less than 1 to 59 percent. Except for a few units, herbaceous plants comprised almost all of the cover in the first year. Values ranged from less than 1 to 57 percent, with half the units ranging from 5 to 27 percent herb cover. Herb cover increased rapidly for the first few years, particularly where fast-growing species such as fireweed *(Epilobium angustifolium)* were abundant members of the seral community. Herb cover usually reached maximum value by the second or third year, with coverages between 25 and 67 percent. Thereafter it leveled off or often declined 5 to 25 percent. This pattern of development for the herb component occurred whether or not there was a concurrent development of shrubs. On a few units this pattern was modified because fireweed and other rapidly developing species were absent. On these, the initial increase in cover was less rapid and peak development was delayed.

SHRUB SUCCESSIONAL STAGE

On most units, first-year cover values by shrubs were low, in the range of 0 to 3 percent. Early development of shrubs was slow but continuous while the community was in the herb stage and often dominated by fireweed. In this respect, shrub development contrasts markedly with herb development. Because most shrub growth is cumulative, its rate of increase grows with the passage of years. Thus, shrubs did not become the predominant component on units on which fireweed was the major herbaceous precursor until at least the sixth year of succession (fig. 15). Five units with this pattern reached the shrub stage in the sixth to eighth year, with coverages of 29 to 55 percent. This pattern of shrub development is characteristic of the Miller area, which contained four of the five units.

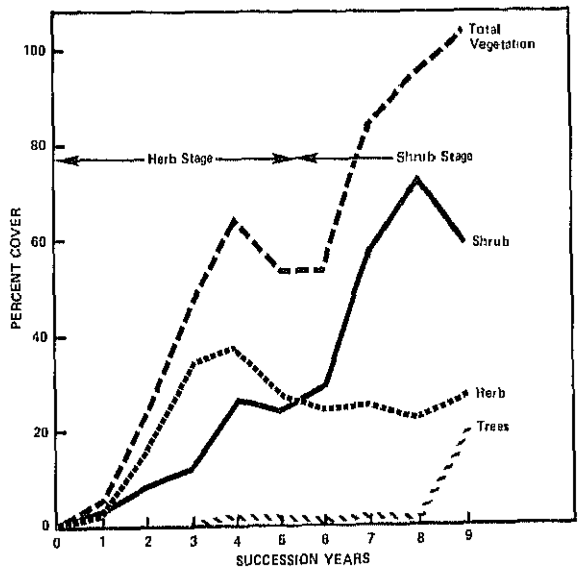


Figure 15.—Development of trees, herbs, shrubs, and total vegetative cover for 9 years following wildfire in standing timber (Miller S-13).

A variant of this pattern characterizes seral development of shrubs at Newman. Most units at Newman had higher coverages (7 to 17 percent) of shrubs in the first year. Development of the shrub component here closely paralleled that of the herb component for the first 3 or 4 years, then increased abruptly to become dominant in the fourth to fifth year, with coverages of 28 to 52 percent (fig. 16). Fireweed was absent or sparse on these sites.

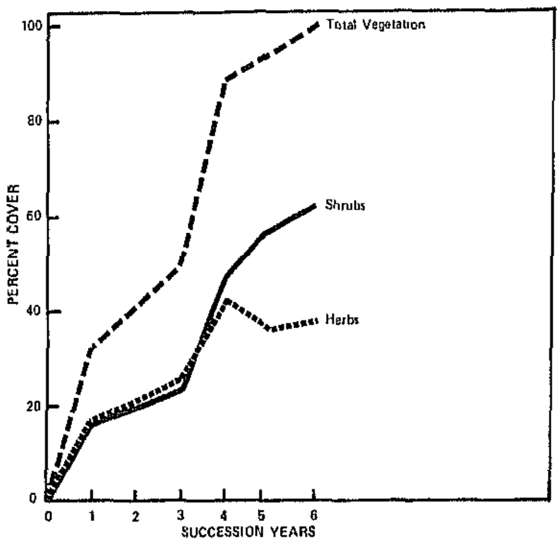


Figure 16.—Development of herbs, shrubs, and total vegetative cover for 6 years following an intense broadcast slash fire at Newman (S-3).

COMPOSITION OF LIFE FORM COMPONENTS

The herb and shrub components of the seral vegetation at Miller and Newman are characterized by 12 species. The forbs include: fireweed, broadleaf arnica *(Arnica latifolia)*, common beargrass *(Xerophyllum tenax)*, pinegrass *(Calamagrostis rubescens)*, northwestern sedge *(Carex concinnoides)*, autumn willowweed *(Epilobium paniculatum)*, and longtube twinflower *(Linnaea borealis)*. The shrubs include: snowbrush ceanothus *(Ceanothus velutinus)*, birchleaf spirea *(Spiraea betulifolia)*, blue huckleberry *(Vaccinium globulare)*, western thimbleberry *(Rubus parviflorus)*, and Scouler willow *(Salix scouleriana)*. All are native to this area. Some 42 percent of the total species are herbs or low woody plants. Rhizomatous species (fireweed, broadleaf arnica, pinegrass, and northwestern sedge) comprise more than half the herbs. Beargrass appears as a tussock plant but actually has a stout surface rhizome, willowweed is an annual, and twinflower is a mat-forming, low, woody plant. Three of the five shrub species (birchleaf spirea, blue huckleberry, and western thimbleberry) are rhizomatous low shrubs. The remaining two, snowbrush ceanothus and Scouler willow, are medium to tall root-crown shrubs.

Prefire resident species (five herbs: broadleaf arnica, common beargrass, pinegrass, northwestern sedge, and longtube twinflower; and three shrubs: birchleaf spirea, blue huckleberry, and western thimbleberry) comprised two-thirds of the postfire plant community. Of the remainder, three species invaded (fireweed, autumn willowweed, and Scouler willow), and one shrub (snowbrush ceanothus) was present as buried seed.

EFFECT OF FIRE

Despite similarity in appearance after fire, the effectiveness of burning (heat treatment) on the regenerative parts of plants showed a wide range over the 20 units studied. In general, the units at Newman received hotter treatments than those at Miller. This concept of burning treatment is a relative measure of the effectiveness of the heat imparted to a narrow zone both above and below the mineral soil surface. It is here that the surviving portions of most forest plants are located that permit their regeneration. A combination of lower duff water content and fire intensity (heat pulse to site) provides a rudimentary expression for the quantification of burning treatment. A highly effective (hot) burning treatment would result from a combination of dry duff (<50 percent water content) and a high fire intensity (>800 grams water loss from water can analogs [Beaufait and others 1977]). In contrast, a relatively ineffective (cool) burning treatment would result from a combination of wet lower duff (water content >100 percent) and low fire intensity (<500 grams water loss). The characteristic effects of a hot treatment are: (1) near to complete destruction of aerial portions of understory vegetation, (2) high mortality of surface and near-surface rhizomatous plants and fire susceptible root-crown plants, and (3) total to nearly complete reduction of the litter-duff layers.

A comparison of two south-facing units at Miller illustrates the effect of differing burning treatments on postfire vegetation in the *Xerophyllum* phase of the *Abies lasiocarpa/Clintonia* habitat type. The preburn forest was similar in structure and species composition, with an overstory composed of nearly equal proportions of Engelmann spruce, western larch, and Douglas-fir, and an understory of subalpine fir. Undergrowth in both was primarily huckleberry and beargrass. One unit was clearcut and broadcast burned; the other unit burned as standing timber by a wildfire. Burning treatment data for the clearcut and burned unit was: lower duff water content of 135 percent, and water can water loss of 286 grams (a cool burn); that for the wild unit was: lower duff water content of 56 percent, with no data for water loss, but fire intensity was great enough to completely consume the duff layer (a hot burn). All fine fuels in the slash and undergrowth vegetation on both units were consumed. On the broadcast-burned unit a charred but nearly continuously intact duff

layer remained. This layer contained many "duff-cracks" from drying out after the fire. On the wildfire-burned unit all trees were killed and the ground surface was covered with ash and charred woody debris. No duff layer remained in evidence.

On the clearcut plot the herb stage reached its maximum cover (61 percent) by the third year and was still dominant after 9 years (fig. 17) Fireweed and beargrass constituted most of the herb cover (fig. 18). Huckleberry and two other resident shrubs, plus Scouler willow, an immigrant pioneer, made up the shrub component. All are slow developing shrubs.

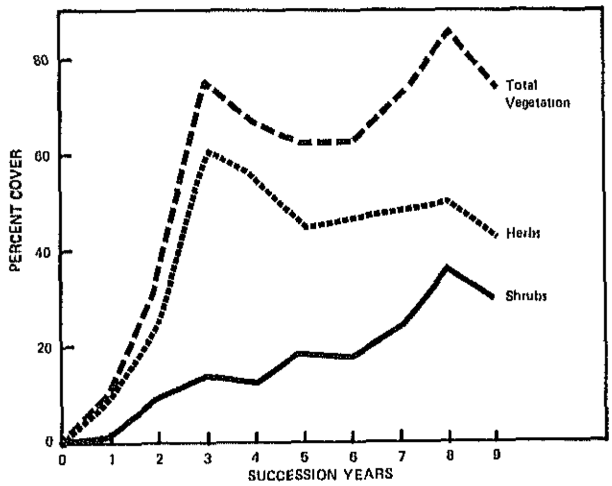


Figure 17.—Development of shrubs, herbs, and total vegetative cover over a 9-year period following a low-intensity slash fire at Miller (S-1).

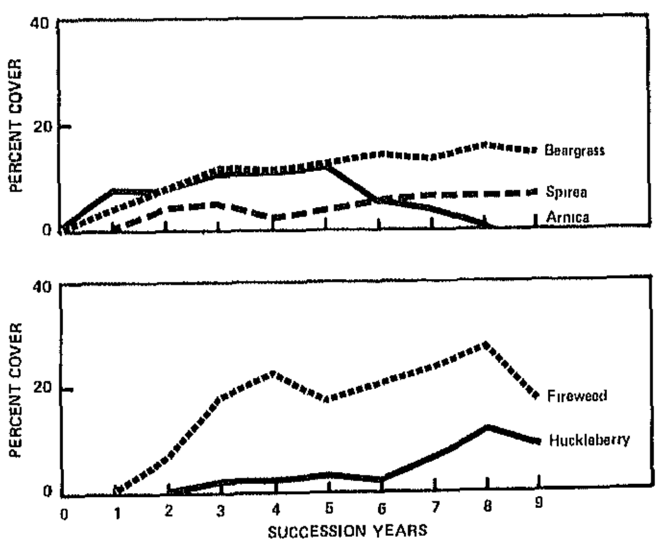


Figure 18.—Development of five prominent plant species following a low-intensity broadcast slash fire on Unit S-1 at Miller.

Plant succession on the wildfire unit also began with an herb stage dominated by fireweed and beargrass, but it was shorter in duration. A shrub component of spirea and Rocky Mountain maple *(Acer glabrum)* exceeded the herb cover by the sixth year (fig. 15), and 2 years later snowbrush ceanothus, a rapidly developing pioneer shrub, became the most abundant cover. Though blue huckleberry was the predominant species among preburn shrubs (with more than 50 percent cover), its postburn recovery has been exceedingly slow. It did not exceed 1 percent cover until the eighth year. Pioneer tree cover was composed of lodgepole pine and western larch. Both became evident as cover in the fourth year (fig. 15). During this initial development stage, the increase in tree cover has been slow relative to the shrub and herb components. While trees remain the least important, they have the potential to shortly displace the shrubs in the wildfire area.

RESPONSE TO BURNING

Some 75 plant species contributed to understory cover before and after burning on the studied units at Miller and Newman. Of these, 16 species accounted for most of the vegetation and thus set its character and mode of development. These principal species each had a cover value of 15 percent or more for at least a year. Principal species consisted of residents and immigrants. Pacific yew *(Taxus brevifolia)* was the only principal resident species eliminated by fire. Before treatment, this prominent tall shrub occurred on 80 percent of the units at Miller with coverage of 1 to 63 percent. After burning it failed to reappear on any of them. While all remaining principal resident species survived, their response to burning varied. The group that responded slowest, and has yet to regain its principal species status, includes the shrubs, rusty menziesia *(Menziesia ferruginea)* and Rocky Mountain maple, and the herbs, goldthread *(Coptis occidentalis)*. These are fire sensitive plants. Their survival was low, their redevelopment was slow, and their percent cover remains well below preburn levels. The more effective burning treatments reduce their survival and slow their response. A second group, including spirea (low shrub), pinegrass (fig. 19), northwestern sedge (both herbs), and twinflower (low woody plant), showed the opposite response. Fires of light to moderate intensity did not kill these plants, but created a favorable habitat for their postfire development. Increases in cover by the fifth to ninth year placed them well above preburn levels.

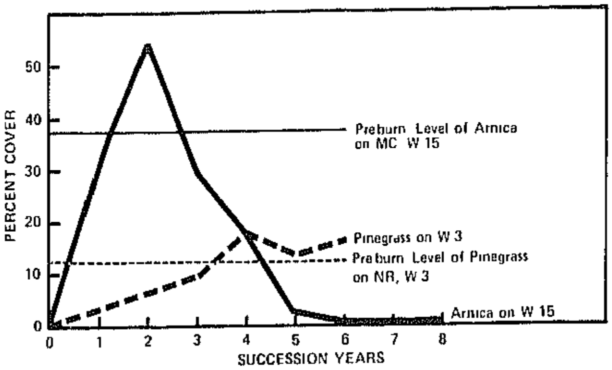


Figure 19.—Maximum development of two resident herbs (arnica and pinegrass) that commonly increase after fires.

Four resident species showed a mixed response to burning. Postfire coverage was higher than prefire coverage on some units and lower on others. In most instances, fire intensity accounts for these variations in response. Huckleberry, the only shrub occurring on all 20 units and present as a principal species on 70 percent of them, had an intermediate rate of cover development. On only two did it regain principal species status. Its recovery on half of the units was between 25 and 50 percent of prefire levels. Response of blue huckleberry to fire is discussed by Miller (1977).

Beargrass, with its surface rhizomes, is quite sensitive to fire. On burns in which the duff layer was left intact, its cover development exceeded preburn levels. But, on units on which fire removed or greatly reduced the duff layer, its cover development had not achieved preburn levels after 7 to 9 years.

Response pattern for thimbleberry is that of a pioneer shrub. It appeared as cover on 60 percent of the postburn units, which is almost twice as many as was its preburn occurrence. Its coverage was several times that of preburn levels on most units, and on two it reached principal species status during the 9 postburn years.

Broadleaf arnica (fig. 19) responded to fire with rapid initial growth during early postfire years, producing sharp increases in cover and an unusually abundant flower crop, usually in the second year. Then, after seed production, its cover declined and remained at low levels.

Two principal, essentially resident species did not survive the fire as living plants, but reestablished or maintained their presence in the community from seed. They are snowbrush ceanothus and lodgepole pine. Both are pioneer species characteristic of early seral stages of forest succession. Ceanothus was not present in the prefire vegetation on any of the units. After burning, it appeared in the first year as large numbers of new seedlings on six of the units All these units had southerly exposures and all received highly effective (hot) burning treatments. Ceanothus has smooth, round, relatively heavy seed that precludes high mobility. It had to be present in the ground at the time of burning to produce the high seedling densities measured. Currently it represents the predominant plant cover on these six units and is largely responsible for their early entry into the shrub stage. On four units at Newman the cover development of ceanothus was evident in the first year due to high seedling densities (fig. 20). It continued to rapidly increase in cover through the sixth and seventh year (the last years of record), becoming the predominant cover plant in the fourth to seventh year. At Miller, ceanothus appeared only on areas burned in the wildfire. The pattern of development there was similar to Newman, differing mainly in a slower initial development. At Miller it was not detected as cover until the third year (fig. 20). Afterwards ceanothus grew rapidly, becoming the predominant cover in the eighth to ninth year.

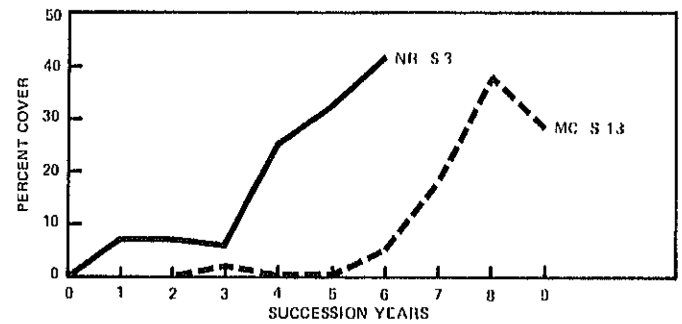


Figure 20.—Development of snowbrush ceanothus after wildfire in standing timber at Miller (S-13) compared to an intense broadcast slash fire at Newman (S-3).

Mature lodgepole pine trees were present on areas with standing timber burned by the wildfire. They provided the source for seedlings that appeared in the first postburn year. Relative to snowbrush ceanothus, cover development by lodgepole seedlings was very slow, reaching principal species status by the ninth year on only one unit.

Postburn vegetation contained three principal species that immigrated from outside the burned area. Fireweed, autumn willowweed, and Scouler willow were not found prior to burning. All three are pioneer species that have small, light, downy seeds that permit long distance airborne dispersal. Next to huckleberry, fireweed was the

most widely distributed postburn species, occurring on all but one of the units. It was the most abundant early seral plant, consistently having greater cover during the herb stage than any other. The extent and magnitude of the herb stage is largely attributable to this species.

The greatest coverage of fireweed occurred at Miller on moist sites with very effective (hot) burns. Well-established stands on these favorable sites exhibited a distinct development pattern (unit E-6 in fig. 21). Following establishment in the first year after burning, its cover increased very rapidly, reaching maximum values by the second or third year. Thereafter, fireweed cover declined to less than half of peak values by the sixth year. On less favorable sites (drier conditions) the pattern differed; maximum cover values developed slowly and were not as high (unit S-1 in fig. 21).

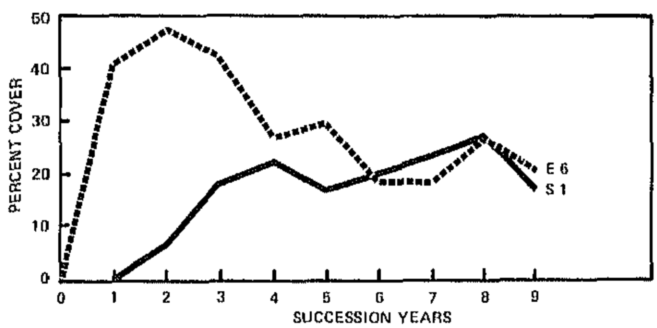


Figure 21.—Contrasting development patterns for fireweed at Miller following an intense slash fire (E-6) versus a low-intensity slash fire (S-1).

Autumn willowweed, a native annual, attained principal species status on only one unit and then for only 2 years. Characteristically, its occurrence as a cover species after fire is short, usually appearing in the second year and lasting 2 or 3 years. Thereafter it continues to be present but always at cover values less than 1 percent. Though brief in its successional appearance, it has the potential to make a significant contribution to vegetative cover in the first few years of succession when total plant cover is low. On the unit where it reached maximum cover in the second year, it provided the greatest amount of cover of any species.

Scouler willow was not found on any of the inventoried units before burning but its seedlings occurred on 80 percent of the units after burning. The rate of cover development by seedlings of this pioneer shrub is quite slow. It had reached the principal species level on only one unit by the ninth year. Earliest detection as cover varied from the second to the seventh year Initial development is one of slow but continuous increase. After 6 to 9 years willow cover on all but two areas was less than 10 percent.

Figures 22, 23, and 24 illustrate the development of vegetative cover on several study units at Newman Ridge and Miller Creek.

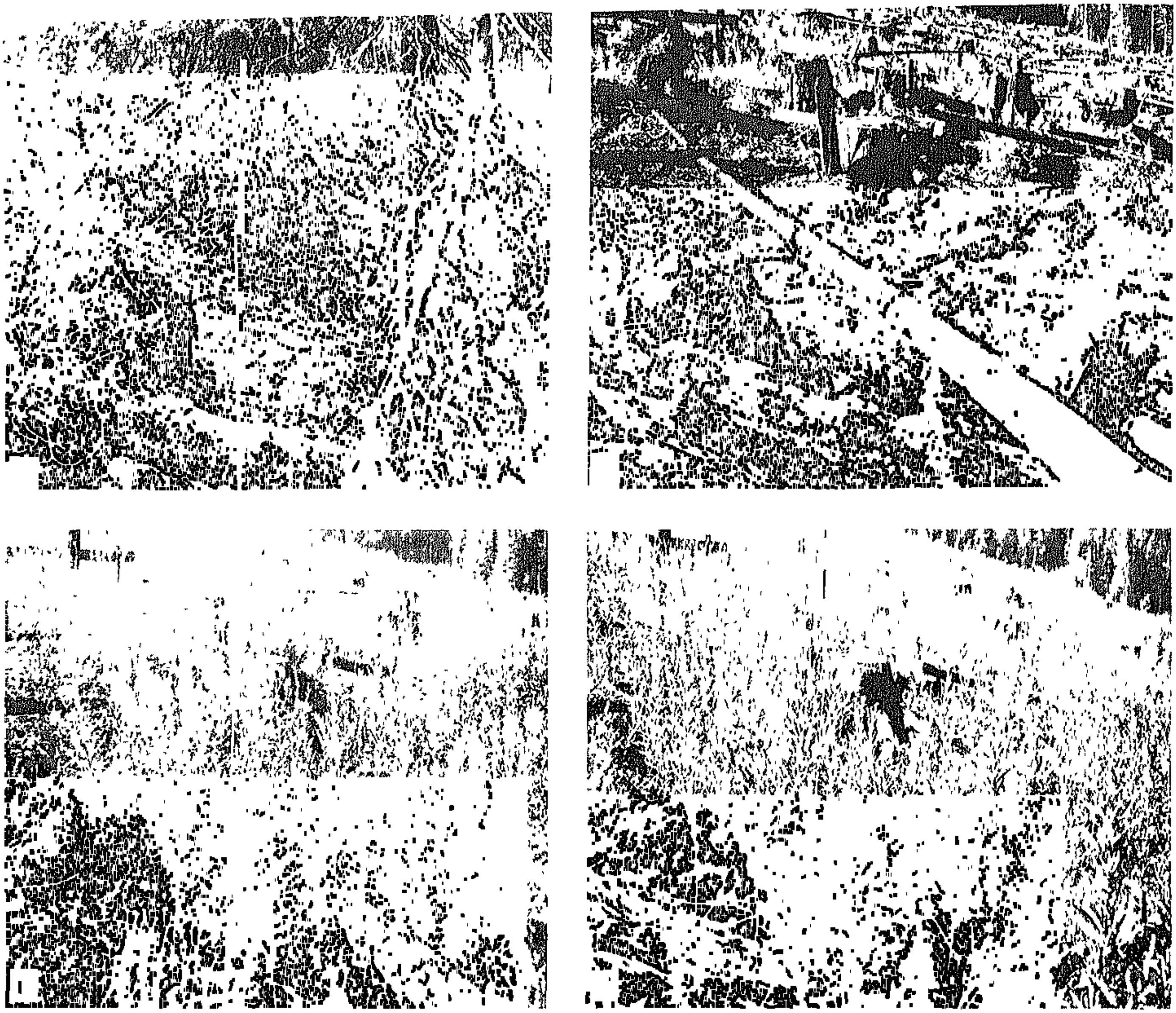


Figure 22.—Miller unit N-8 before treatment (a), 1 year after logging and broadcast burning (b), 2 years after (c), and 5 years after (d). Shrub development was slow; after 7 years (1975) this transect still appeared as it does in "d," with fireweed the dominant herb.

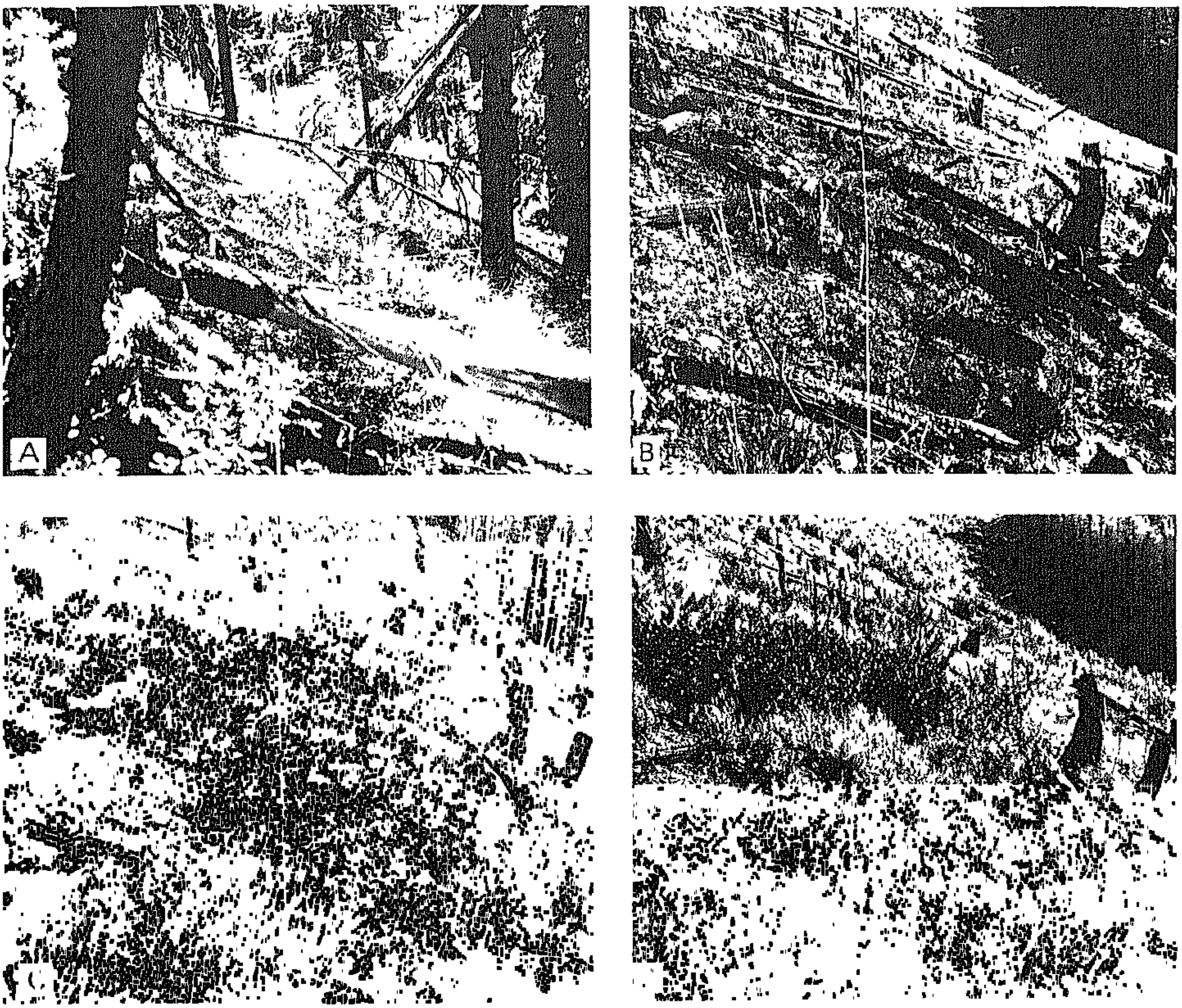


Figure 23.—Newman unit W-3 before treatment (a), 1 year after logging and broadcast burning (b), 4 years after (c), and 6 years after (d). Progression to the shrub stage is obvious in "d," with some tree seedlings also visible.

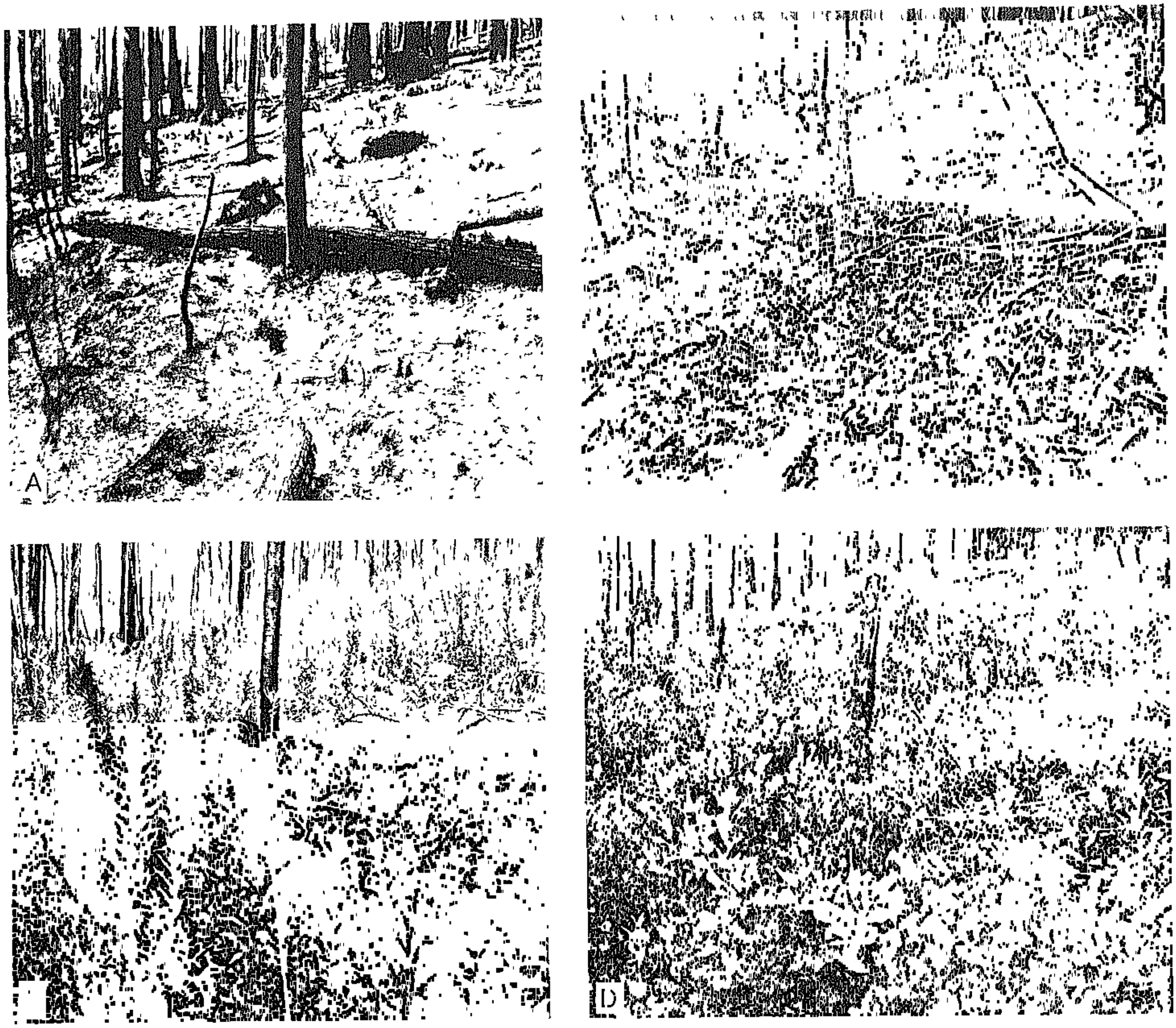
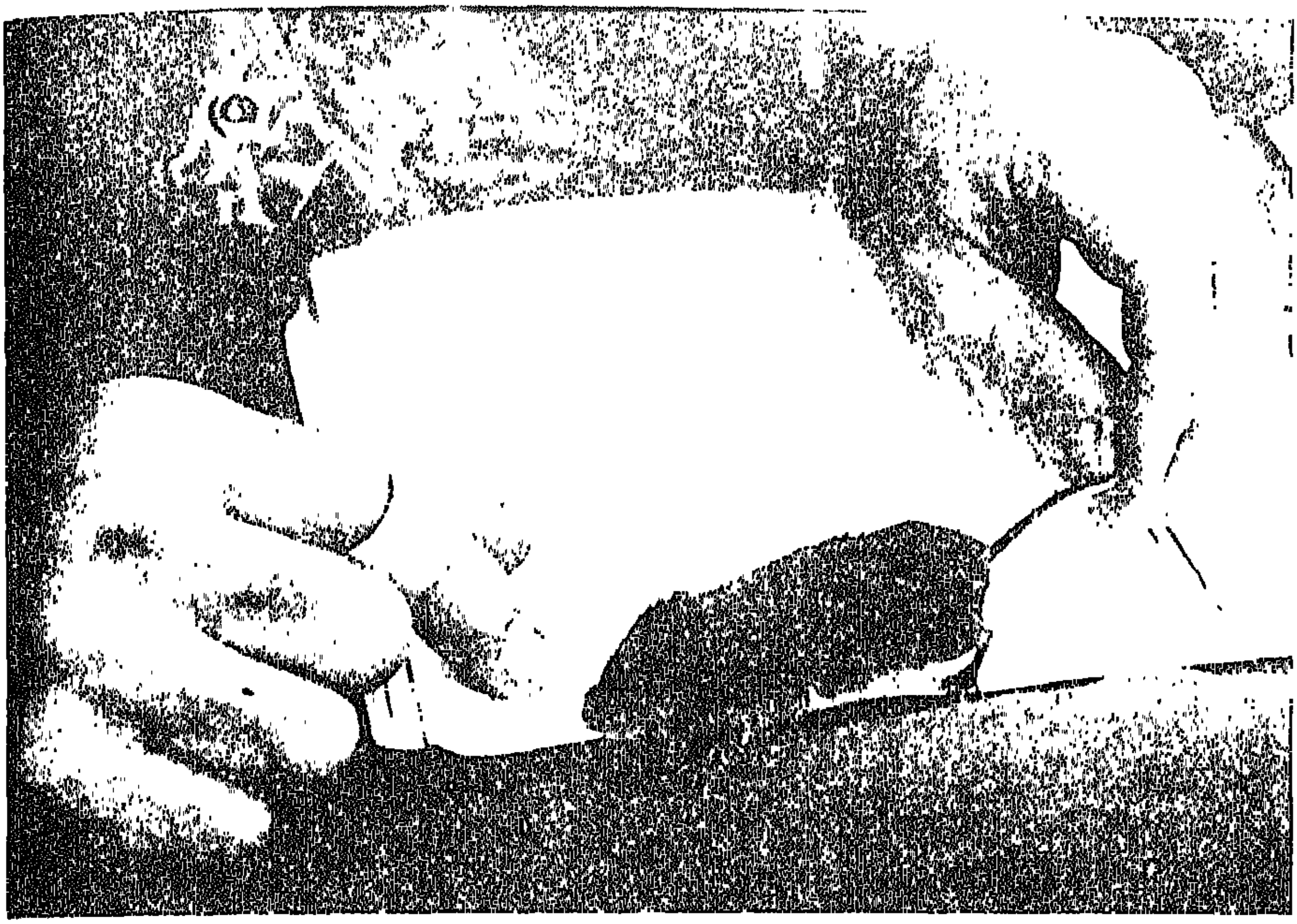


Figure 24.—Miller unit S-12 immediately after wildfire (a), 1 year later (b), 3 years after (c), and 8 years after (d). After passing through an early herb stage, dominated by fireweed, (c), succession to shrubs and trees was rapid on this area (d).



Long-tailed vole trapped on a clearcut unit at Newman. (USDI Fish and Wildlife Service photo)

Small Mammal Populations

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Small mammals, chiefly rodents, are the most numerous large primary consumers of plant energy. Their predilection for conifer seeds and seedlings as food makes these rodents of interest to forest managers. Deer mice (*Peromyscus maniculatus*), chipmunks (*Eutamias* spp.), and red-backed voles (*Clethrionomys gapperi*) are especially important consumers of conifer seed (Radvanyi 1973). Small mammals, most of which are active yearlong, usually have two or more litters per year. Young mature in 2 or 3 months; populations turn over rapidly. Population rotations, especially among mice, are only 9 to 18 months long. Some species are cyclic in numbers, apparently responding quickly to food increases, favorable habitat change, and weather effects. Small mammals live in a microclimate within 18 inches (46 cm) above the ground surface to somewhat below. A small rodent spends most of its life on less than an acre. Worldwide, small mammals are the most important food source for terrestrial carnivores—both birds and mammals. They may be important indicators of forest habitat condition.

Species composition and relative abundance of small mammals on selected units at Miller and Newman were determined and related to patterns of plant succession and cover conditions for

several years after clearcutting and broadcast burning.

Of 11 small mammal species caught, the most common and abundant rodents at Newman and Miller were the deer mouse and the redtail chipmunk (*Eutamias ruficaudus*). They, along with the ermine (*Mustela erminea*) and vagrant shrew (*Sorex vagrans*) were found on all sites—undisturbed timber, logging slash, and light and severe burns. The ermine and shrew appeared in very small numbers, however. In terms of total individuals caught, deer mice, chipmunks, and red-backed voles constituted 90 percent of more than 1,800 small mammals caught on the two areas during the period 1967 through 1974. The red-backed vole did not have the same distribution as the other species, as will be discussed. These three rodents readily consume and store conifer seed, the vole is also adapted to using succulent vegetation.

SMALL MAMMAL POPULATIONS IN OLD-GROWTH TIMBER

The mature, uncut forest and its small mammal populations serve as the reference base to assess impacts of logging and burning. Figure 25 averages 6 years of live-trapping on the forested control plots on Newman. It includes the year of abundant conifer seed (1971), and the fluctuations in red-backed vole, chipmunk, and deer mouse numbers. This 6-year average catch, by species, illustrates the variation that may be expected in small mammal populations of old-growth larch/Douglas-fir stands.

The most abundant rodent in old-growth timber was the red-backed vole. In contrast, it was virtually absent on burned plots (fig. 25). Its relative stability and abundance on the north-facing plot suggests a very favorable environment. The red-backed vole is considered a forest species showing strong association with damp conditions (Getz 1968; Gunderson 1959; Odum 1944), as well as rotting log and stump cover (Gunderson 1959; Williams 1955).

The second most common timber inhabitant was the chipmunk, a rodent partial to some cover (Tevis 1956) and drier sites. Comparison of the 6-year means (fig. 25) shows chipmunks twice as common in the drier south timber plot. This is in keeping with its recognized habitat association.

Deer mice were an important component on all plots (fig. 25). But, like chipmunks, they were more common and their numbers varied less between years on the drier south aspect. Thus, they

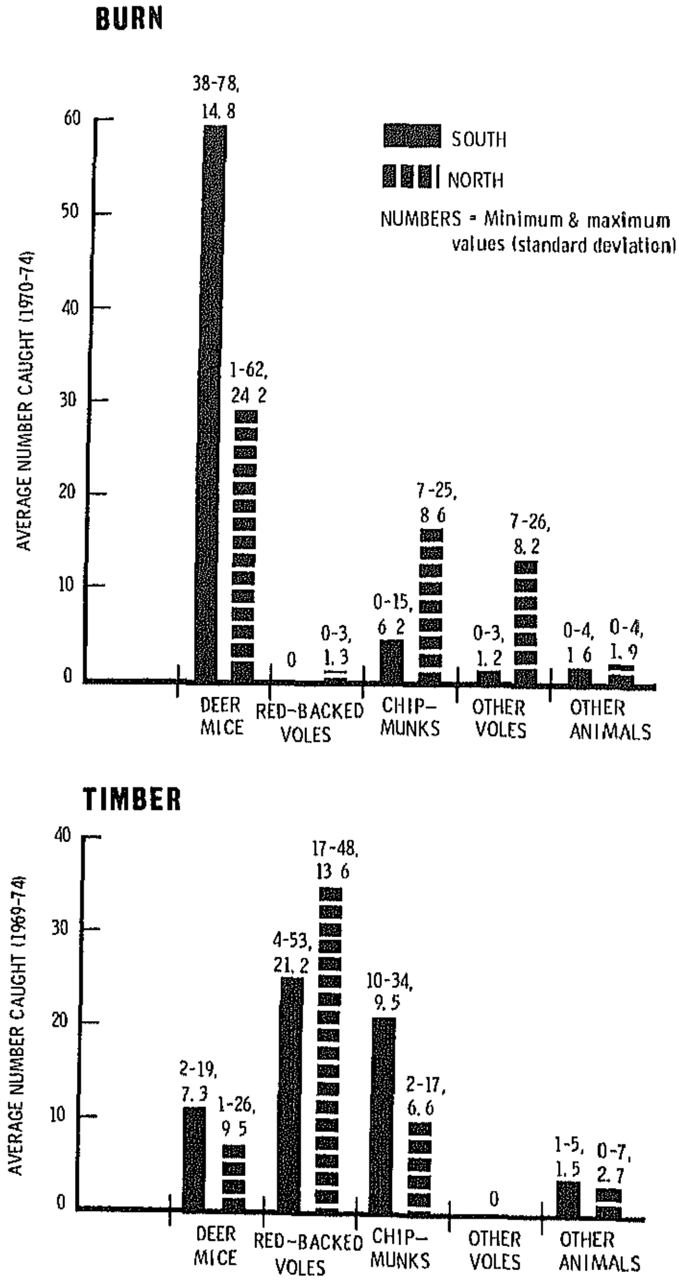


Figure 25.—Average number of small mammals caught at Newman. Uncut timber is compared to broadcast slash burned units on north (N-3) and south (S-3) aspects.

exhibited the same population response in their preferred (drier) environment as did the red-backed vole in its favored (wetter) habitat. Simply put, larger and more stable populations are found in preferred habitat. No other mouse or vole species were caught in the timber at Newman or at Miller. They were undetectable at the sampling level used. Their detection on burns (fig. 25) indicates that they must have been present, albeit sparsely, in the uncut forest, too.

Other animals (fig. 25) appear in about equal numbers. The few that were caught merely indicate their presence. They include the ermine, vagrant shrew, northern flying squirrel (*Glaucomys sabrinus*), red squirrel (*Tamiasciurus hudsonicus*), and bushy-tailed woodrat (*Neotoma cinerea*). Three of these, the ermine, flying squirrel, and shrew, respectively, were 2, 3, and 10 times more often caught in the south-timber than in the north-timber plot at Newman. The flying squirrel's critical habitat includes nesting cavities in large and durable snags. Snags of western larch and ponderosa pine best embody these attributes of size and durability. The north-timber plot had no ponderosa pine whereas the south had both pine and larch.

Table 11 compares and summarizes the relative importance of small mammal species in old-growth timber at Newman and Miller. Even with the small Miller sample, the dominance of red-backed voles in timber is still obvious. A similar relationship within and between these widely separated study areas is also seen for chipmunks, deer mice, and "other voles." Within the complex, mature timber habitat, chipmunks were more common than deer mice, "other voles" were absent, and "other animals" were in greater abundance. Ninety percent of "other animals" at Miller were shrews.

POPULATION CHANGES AFTER CLEARCUTTING AND BURNING

Treatment resulted in marked and comparable changes in small mammal species composition at both Miller and Newman (table 11). Deer mice rose from less than 20 percent composition to over 70 percent. Red-backed voles disappeared. Other vole species, mostly the long-tailed vole (*Microtus longicaudus*), appeared in catches for the first time. Chipmunk presence was reduced by at least 30 percent.

Clearcutting a closed-canopy forest, broadcast burning residual slash and understory vegetation, and raising soil surface temperatures to over 500°F (260°C) are catastrophic changes to the small mammal habitat. Broadcast fires seldom persist very long, nor blanket an area uniformly, nor with an even intensity because of varying fuel distribution and moisture on clearcuts. There are hot and there are cool spots.

Table 11.—Comparison of small mammal species composition in uncut timber and clearcut burns on Newman (1969-74) and Miller (1967-74)

Species	Timber				Burn			
	Newman[1]		Miller[1]		Newman		Miller[2]	
	Percent	*No.*	*Percent*	*No.*	*Percent*	*No.*	*Percent*	*No*
Deer mice	16	111	10	6	70	440	74	413
Chipmunks	26	183	25	15	16	104	8	42
Red-backed voles	52	356	44	27	1	3	2	14
Other voles	0	0	0	0	11	71	12	67
Other animals[3]	6	42	21	11	2	14	4	23
Totals	100	692	100	64	100	632	100	559

[1]All aspects combined, by treatment. Miller Creek is only a one-time (1967) sample.
[2]Does not include two unburned clearcut blocks.
[3]Shrew, ermine, flying squirrel, red squirrel, woodrat, and snowshoe hare (*Lepus americanus*)

Most rodents nest underground, sometimes several feet below the surface. Soil is an excellent insulator. Despite the 500°F (260°C) surface soil reading on the S-3 plot on Newman, subsurface temperatures at 2 inches were 118°F (60°C) (Ray Shearer, personal communication). Field experiments with caged rodents buried underground have shown the lethal level to be 140°F (60°C) (Howard and others 1959) to 121°F (49°C) at relative humidities below 50 percent (Lawrence 1966). Fire does not necessarily deny food to rodents, especially spermivores (seed-eaters), since caches and naturally fallen seed accumulated over time (such as from snowbrush ceanothus) or disseminated after the fire (such as from lodgepole pine) are available. Fungi, including hypogeous (subterranean) types, are always present and widely used by many small mammals (Maser and others 1978). Insects, an important food for many rodents, especially deer mice and shrews, quickly emerge after the fire or reinvade the site. Corms and bulbs virtually always survive fire, and rhizomes and root crowns usually do. All are postfire food sources.

Removal of the forest probably had the most profound effect on mammals; fire was of secondary importance. Unfortunately, the study design did not allow a clear distinction between the effects of forest removal and the effects of fire. Clearcutting drastically altered arboreal nesting habitat, removed much escape cover and physical shelter, and changed the microclimate (humidity, surface temperature, soil moisture, and wind movement) in the zone occupied by small mammals.

The N-3 and S-3 units on Newman provide some insight into the effects of fire intensity. Unit S-3 burned hot and clean in mid-September, whereas unit N-3 burned poorly only 2 weeks later. Only 35 percent of the surface of N-3 was touched by fire. Wet duff kept the burn relatively cool. So, the most pronounced environmental effects on S-3 were the result of clearcutting plus a hot slash fire, while those on N-3 were largely the result of clearcutting and minimally that of fire. Rodent trapping was being done on the adjacent timbered control plot when S-3 was burned. Trapping began 2 weeks later on the burned units.

Ninety-five percent of the animals caught on S-3 (the hotly burned unit) in the first 3 years were deer mice (fig. 26). As cover developed a few chipmunks and other mouse species moved in, but they never exceeded 10 percent of the catch. It is important to note that all rodents caught on S-3 two weeks after burning were deer mice. Their populations in adjacent timbered areas were extremely low at the time, strongly suggesting that large numbers of deer mice were present in the year-old slash on S-3 and that they survived the fire in place. Densities varied from 6 to 12 per acre. Deer mice are a pioneering species strongly associated with seral situations (Williams 1955).

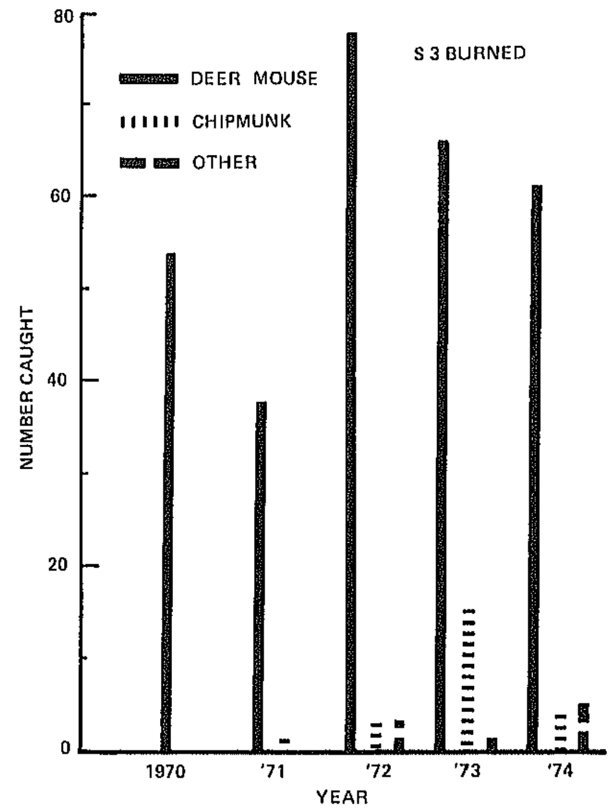


Figure 26.—Numbers of small mammals caught, by species and years, on unit S-3 at Newman. Logged in June 1969, intense slash fire in September 1970.

By contrast, deer mice on the cooler burned unit (N-3) have been of lesser relative importance, although they were still the most abundant rodent caught (figs. 25 and 27). The N-3 burn provided a diversified environment, including moist shaded areas, a variety of forbs and fruit, and seedbearing shrubs. Under these conditions, population growth of deer mice was likely restrained by competition from other species occupying niches in the less disturbed habitat on N-3.

Chipmunks were an important part of the catch on unit N-3, even at the time of the fire. After burning, abundant slash remained on N-3. Chipmunks favor cover (Tevis 1956) and, no doubt, preferred this area. Their increase is associated with increasing cover and with fruit and seed producing plants (Gashwiler 1970; fig. 27). The catch averaged over twice that for S-3 in the 1970-74 period (fig. 25).

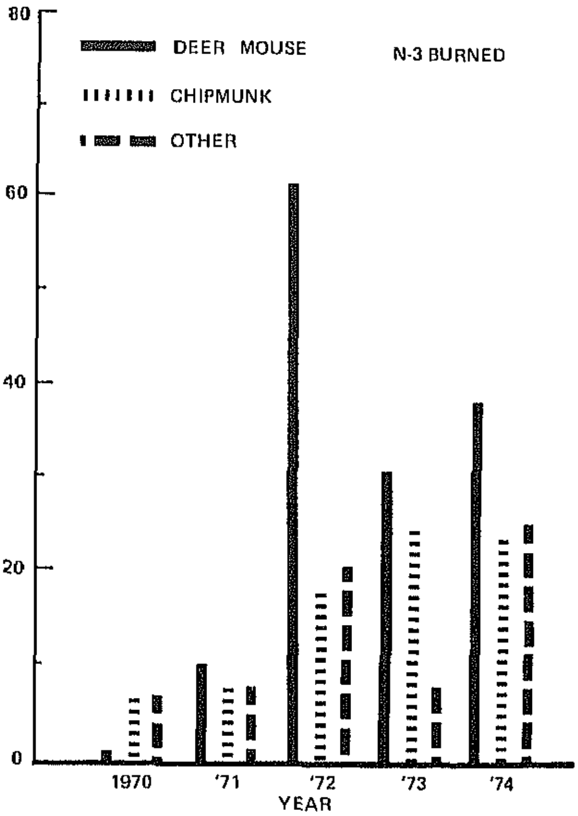


Figure 27.—Numbers of small mammals caught, by species and years, on unit N-3 at Newman. Logged in June 1969, low-intensity slash fire in September 1970.

Long-tailed voles have been the only other mouse-like rodent to appear on unit N-3 (fig. 25). Their occurrence on N-3 apparently results from the existence of the moist sites, where most of them were captured. Habits of this rodent are not well known (Maser and Storm 1970) but it probably is more of a grazer on succulent vegetation than a seed-eater. It was never caught in timber (fig. 25), which suggests that it may be an unsuccessful competitor with the red-backed vole.

The Newman burns (N-3 and S-3) had lower rodent numbers the first 2 years, but since then rodent populations in these units consistently exceeded populations in adjacent timber (fig. 28). The north unit, initially with the lowest catches of any, still had a growing population some 7 years later. Though not proven, the reasons for the population increase after cutting and burning probably are the cumulative effects of more habitat niches, which resulted in a diversity of rodent species, plus development of a vigorous understory flora, which, in turn, responded to release by clearcutting and to the fertilizing effects of leached ash (Ahlgren and Ahlgren 1960; DeByle 1976).

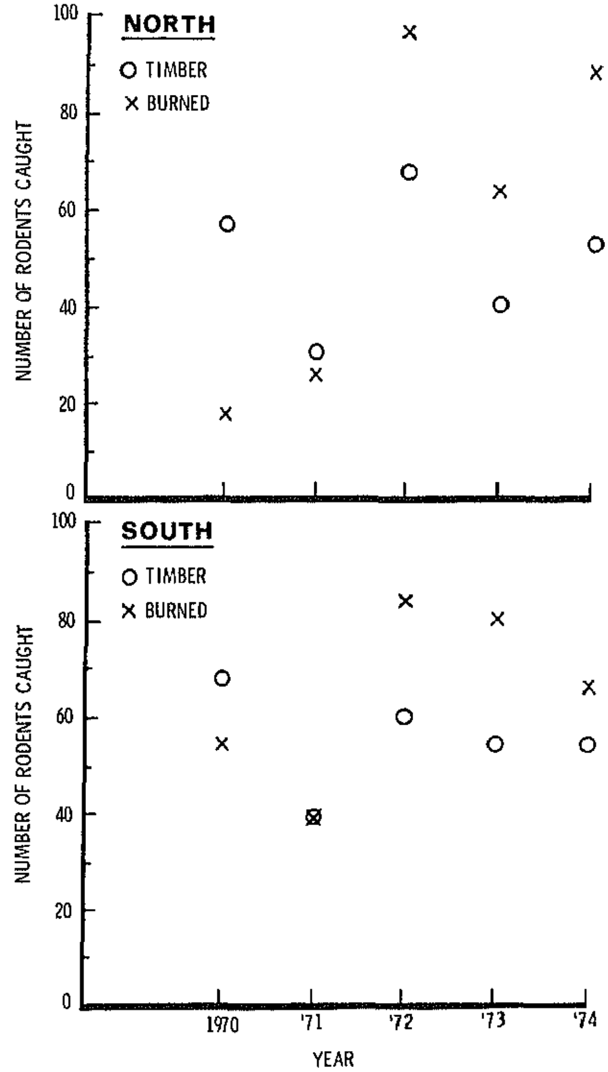


Figure 28.—Annual rodent catch for north and south aspects at Newman, comparing old-growth timber habitat to clearcut and burned habitat.

Rodent numbers were also influenced by a nonfire effect that should be recognized by forest managers who attempt forest regeneration. In the 1969-74 period at Newman the largest catches were in 1972 (figs. 26, 27, and 28), with deer mice (fig. 29) making up the bulk of the catch A heavy seedfall occurred in 1971 (Shearer 197(and in this report). The subsequent rodent in crease corresponds to previous reports (Jamesoı 1953; Gashwiler 1966; Hooven 1976) that dee mice increase the year following a heavy conife seed year.

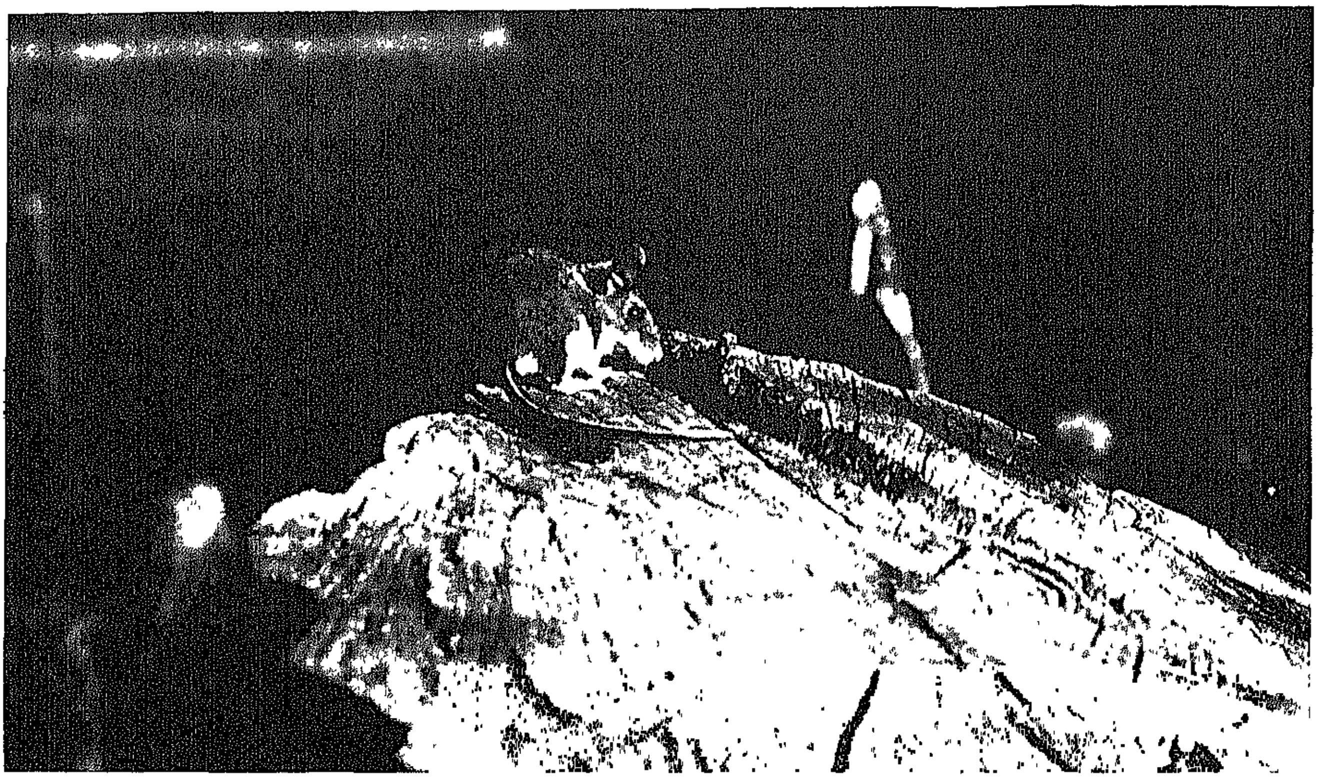
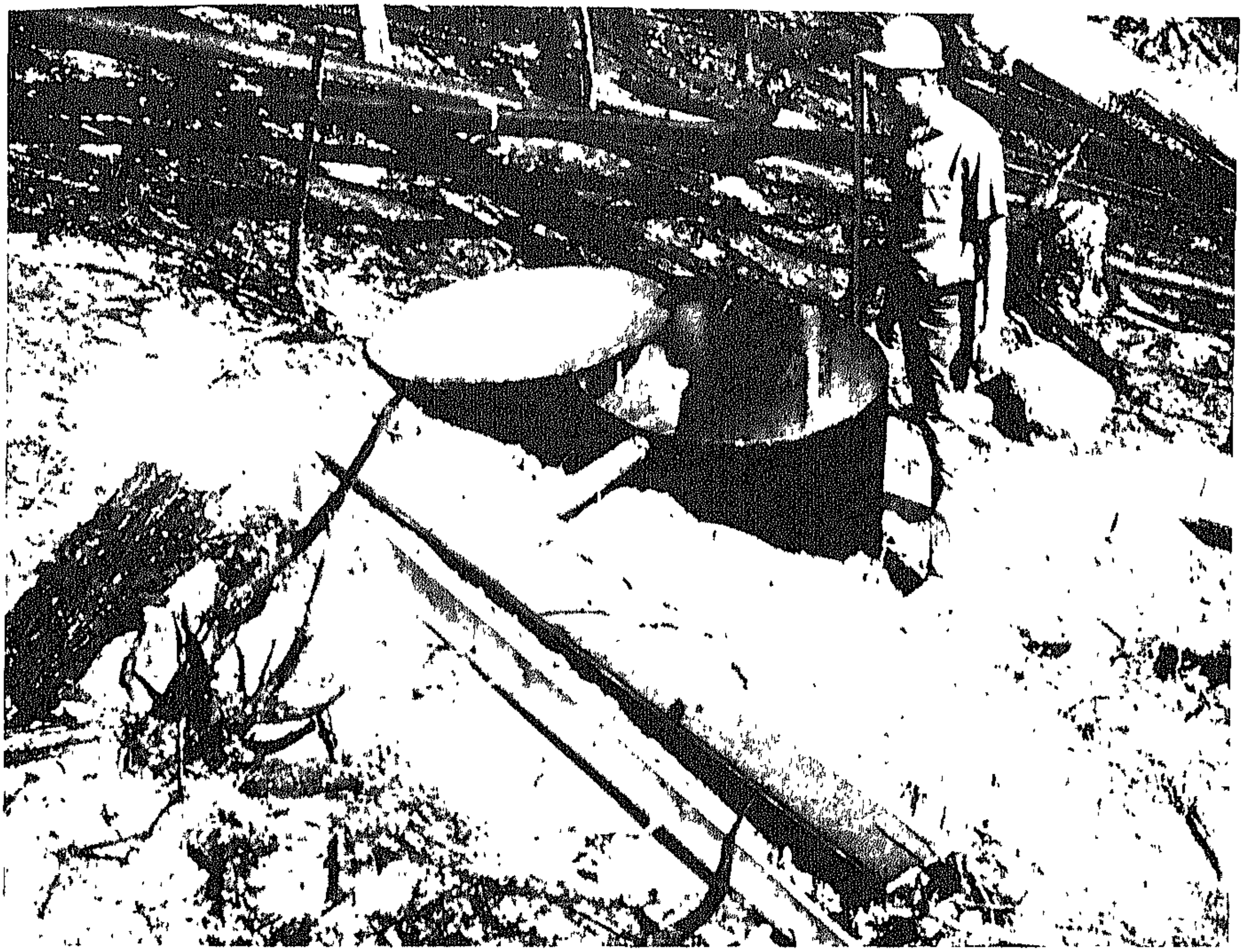


Figure 29.—Deer mice are the most common seed-eating rodent during early years of succession after clearcutting and broadcast burning. (Photo by Halvorson, USDI Fish and Wildlife Service.)



Catchment trough and storage tank installed immediately after burning at the base of a runoff plot at Miller.

Soils and Watershed

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When plant cover is sufficient on these humid watershed lands, very little of the annual precipitation becomes overland flow. Seepage flow through these soils does not adversely affect slope stability, even where steep, as on Newman. Baring of mineral soil surfaces through logging disturbance, fire, road building, or any other process sets the stage for overland flow and erosion of soil and nutrients from these slopes. The effects of clearcutting and burning on soil physical properties, quantity and quality of overland flow, and amount and nutrient content of eroded material were measured for several years on small runoff plots on both study areas.

The annual cycling of plant nutrients is temporarily interrupted by removing much of the plant cover (clearcutting) and then killing what remains (burning). Also, burning converts the nutrients held in the fuels to gaseous products (such as NO_2) or ash. The ash, then, is readily leached of many of these nutrient elements by subsequent rainfall or percolating water from snowmelt. The effects of these processes, as reflected in soil chemical properties, were measured for several years at Miller. The material presented in this chapter summarizes prior publications by these authors, particularly those by DeByle (1976) and Packer and Williams (1976) in the proceedings of the Tall Timbers Fire Ecology Conference No. 14.

PHYSICAL SOIL PARAMETERS

Cover

Before treatment, the mineral soil surface was protected from direct raindrop impact and erosion by a complete blanket or organic material (A_0 horizon) as well as a vegetative canopy. Logging removed the canopy and partially broke up the organic matter blanket.

Burning dramatically decreased total soil cover to less than 50 percent on all the Miller runoff plots. These reductions were greatest on south aspects, which were driest and usually supported the most effective fire. On these plots, a slight decline continued during the first year after burning to less than 40 percent cover. Recovery then was rapid, with herbaceous vegetation, particularly fireweed, making up most of the cover. Between 3 years and 7 years after burning, total cover declined, partly due to a decrease in fireweed. By the seventh year about two-thirds of the soil was protected with vegetation or litter (fig. 30). Perennial vegetation and litter 10 years after treatment appeared to cover at least 75 percent of the ground on these study areas.

Burning decreased the cover to less than 20 percent on the Newman runoff plots. Again, reductions were greatest on south aspects. Following a flush in vegetation growth during the first year after burning and a decline in the second year, recovery of vegetation was rapid and reached about 65 percent by the fifth year after burning.

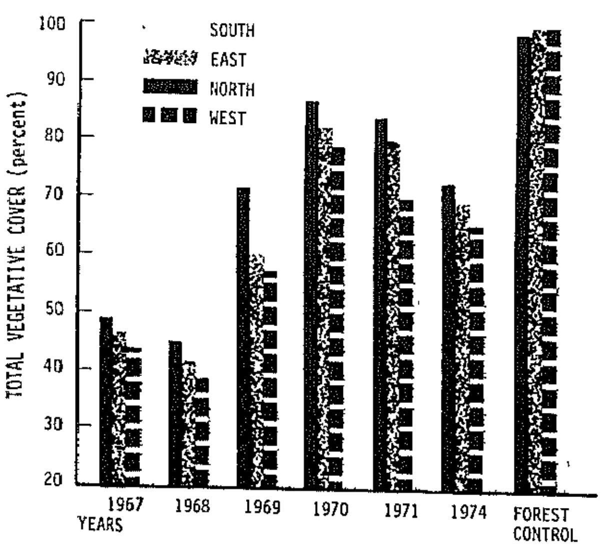

Figure 30.—Effect of logging and broadcast burning on total vegetative cover through 7 postburn years at Miller.

Organic Matter Content

At Miller, logging significantly increased organic matter in the surface inch (25 mm) of soil (fig. 31). Burning decreased it. Organic matter continued to decrease on the runoff plots and on the intensely burned areas for the next 2 years. This postburn decline is partially attributed to wind and water erosion but primarily to decomposition of the residual organic matter during the denuded period following fire, when annual increments of organic debris were negligible. Recovery on lightly burned areas began to occur the first year after burning. On the intensely burned areas and on the runoff plots it began 2 years after burning. The organic matter content of the soil was not affected significantly by logging or burning below a sampled depth of an inch or two (25-50 mm).

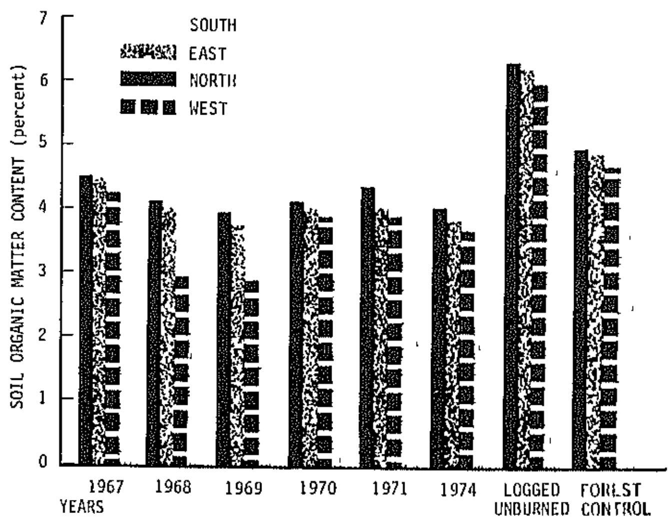

Figure 31.—Effect of logging and broadcast burning on organic matter content of the surface inch of mineral soil at Miller.

At Newman, logging increased organic matter in the surface inch (25 mm) of soil. Again, burning decreased it. During the first year after burning, organic matter increased along with the flush in vegetation, but again declined during the second year. Since then, through the fifth year after burning, organic matter remained almost constant at about 5.2 percent, nearly that on the unlogged, unburned sites.

Porosity and Bulk Density

At Miller, greatest soil bulk density and lowest porosity values were found on the south aspect, with a decreasing trend in density and increase in porosity to west to east to north. These differences existed on both treated and untreated plots; they apparently were not caused by either

logging or fire. Bulk density decreased significantly on all aspects following logging (fig. 32), probably from incorporation of fine logging residue into the soil surface. Burning had the opposite effect, increasing bulk density on all aspects. This likely was caused by partial combustion of some of the fine organic materials previously incorporated into the mineral soil.

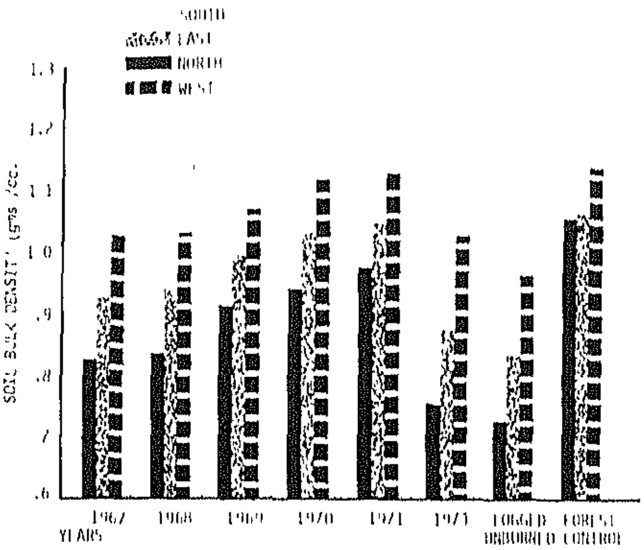

Figure 32.—Effect of logging and broadcast burning on the bulk density of the surface inch of soil at Miller.

During the subsequent 4 years soil bulk density increased still further before reversing and recovering to bulk density values similar to logged but unburned plots in the first year. The smallest decrease, and hence the poorest recovery, has occurred on south slopes.

At Newman, soil bulk density was highest and porosity lowest on the west aspect, with a decreasing trend in density to south to east to north. Bulk density decreased with logging, increased during the first 2 years after burning, and then decreased to its lowest value 5 years after burning. Poorest recovery has been on west and south slopes.

At Miller, logging increased soil porosity, no doubt for the same reason that it decreased bulk density. Burning reduced soil porosity, and it continued to decrease for the next 4 years toward prelogging and burning values. Subsequently this trend reversed and soil porosity increased to greater than prelogging values on all but the south aspects. There it has decreased continuously since the first posttreatment year.

At Newman, soil porosity increased with logging, decreased during the first 2 years after burning, and then increased gradually over the next 3 years. At the end of 5 years it was very nearly the same as porosity on the timbered control plots. Lowest porosities existed on west aspects in the fifth year after burning.

Water Repellency

The decomposing portion of the surface organic horizon (the lower strata filled with fungal hyphae) was very water repellent when dry in midsummer. However, the underlying mineral soil was only occasionally repellent, with most repellency at the interface between the A_0 and A_1 horizons. At least at Miller there was a temporary increase in the percentage of mineral soil samples found repellent after fire, particularly under intense burns. This repellency, however, was lost within a couple years. Fewer mineral soil samples were repellent 1 and 2 years after treatment than were repellent prior to burning.

Broadcast burning of logging debris over a relatively wet soil mantle does not cause sufficient heating of the mineral soil to produce a strongly repellent layer. Furthermore, the high clay content in these particular soils prevented serious repellency even where high enough temperatures were attained. Water repellency in the surface organic mantle does not appear to have practical hydrologic significance on these areas, as there is negligible overland flow and no erosion from the undisturbed forest areas where the organic layer is almost continuous and is thickest.

CHEMICAL SOIL PARAMETERS

The chemical parameters analyzed in the surface foot (30 cm) of soil at Miller before burning, after burning, and for 2 years thereafter are: pH; total contents of nitrogen, phosphorus, potassium, sodium, calcium, and magnesium; available phosphorus; cation exchange capacity; and exchangeable and soluble potassium, sodium, calcium, and magnesium.

Soil pH

Soils are acid, which is typical of the northern coniferous forest. Preburn pH was:

Soil depth		**pH**
Inches	*(cm)*	
0-2	(0-5)	5.6
2-4	(5-10)	5.8
4-8	(10-20)	6.0
8-12	(20-30)	6.1

Burning increased pH in the surface layers. The increase continued during the subsequent year. A year after burning, pH was 6.0 or higher at all depths.

Total Nitrogen

The organic fraction contains most soil nitrogen. The organic material on the surface or incorporated into the surface 2 inches (10 cm) of these soils contained 1 percent nitrogen by weight. Combustion of this organic material volatilizes much of this nitrogen. Nitrogen in the surface organic horizon (A_0) was reduced from 60 g/m² before burning to 40 g/m² after burning A year later it had declined to 36 g/m². Thus more than a third of the nitrogen held in the organic layer was lost directly or indirectly by burning. The nitrogen content of the mineral soil was not altered by burning or during the following year. It remained at approximately 1.0 percent in the surface 2 inches (5 cm) and at 0.08 percent in the 2- to 4-inch (5-10 cm) layer.

Phosphorus

Total phosphorus content of the surface organic layer increased from 5.6 g/m² to 6.5 g/m² after burning. This increase probably came from ash-fall from burned logging debris. Leaching and erosion during the subsequent year reduced phosphorus content to 4 g/m² During the same time there was a slight increase in available phosphorus in the mineral soil, from 78 ppm to 84 ppm in the surface 2 inches (5 cm).

Potassium

The potassium content of the surface organic layer was 14.7 g/m² before burning. Ash-fall from burning increased this to 19.6 g/m². During the subsequent year more than half of this highly mobile element was lost from the surface layer of organic matter and ash, reducing the content to 8.8 g/m². At the same time, the exchangeable potassium content in the mineral soil increased as follows:

Soil depths		Preburn	1-yr postburn
Inches	*(cm)*	*Meq/100 g*	
0-2	(0-5)	0.38	0.47
2-4	(5-10)	.35	.44
4-8	(10-20)	.32	.36
8-12	(20-30)	.23	.26

Sodium

These soils contain comparatively small amounts of sodium. The surface organic layer contained 2.8, 2.9, and 2.1 g/m² before burning, after burning, and a year after burning, respectively. Neither burning nor the conditions the following year caused any significant change in the amount of exchangeable sodium in the mineral soil, but did cause a significant decrease in the amount of soluble sodium.

Calcium

Calcium was the most abundant cation in the surface organic horizon or in the mineral soil. It averaged 72 g/m² in the surface organic layer before burning. A year later there was 66 g/m², statistically the same as before. Exchangeable calcium content of the mineral soil did not statistically change after treatment. Variation among samples was much too great even to infer any possible trends. Soluble calcium in the mineral soil declined slightly during the year after burning, from 0.24 meq/100 g in the surface 2 inches (5 cm) to 0.20 a year later. The minute soluble contents of other cations similarly decreased in the mineral soil, too.

Magnesium

Total magnesium content of the surface organic horizon averaged 15.4 g/m² before burning but only 8 g/m² a year later. Almost half had been removed by leaching, erosion, or plant uptake. Exchangeable magnesium increased significantly during the first postburn year in the surface 4 inches (10 cm) of mineral soil.

Cation Exchange Capacity

The cation exchange capacity of the mineral soil did not change as a result of treatment. It remained near 20 meq/100 g in the surface 2 inches (5 cm) and decreased progressively to approximately 15 meq/100 g in the lower depths. The percentage of this exchange saturated with the four measured cations (Ca, Mg, K, and Na) increased slightly from preburn to a year postburn, from about 38 to 40 percent in the surface 2 inches (5 cm) with similar changes at lower depths.

WATER

The quantity and nutrient contents of overland flow from both spring snowmelt runoff and summer storms were determined for several years using data collected from the 24 runoff plots (12 on each area).

Amount of Overland Flow and Soil Erosion

At Miller, overland flow from snowmelt was negligible the first year after burning, but only 12 inches (305 mm) precipitation was received that winter. Increased precipitation, from 17 to 33 inches (430 to 835 mm), in subsequent winters produced overland flow from the timbered control plots as well as the treated units. None of the control plots produced any soil erosion from snowmelt runoff (fig. 33). Soil erosion from the logged-burned plots averaged 56 lb/acre (63 kg/ha) the first year after burning, then increased to 168 lb/acre (188 kg/ha) the second year, when 18 inches (455 mm) winter precipitation was received. By the third year, soil erosion from snowmelt decreased to 15 lb/acre (17 kg/ha) despite precipitation and overland flow being almost as great as it had been the previous year. Seven years after burning, when more winter precipitation was received than in any previous year, there was no soil erosion from these treated plots.

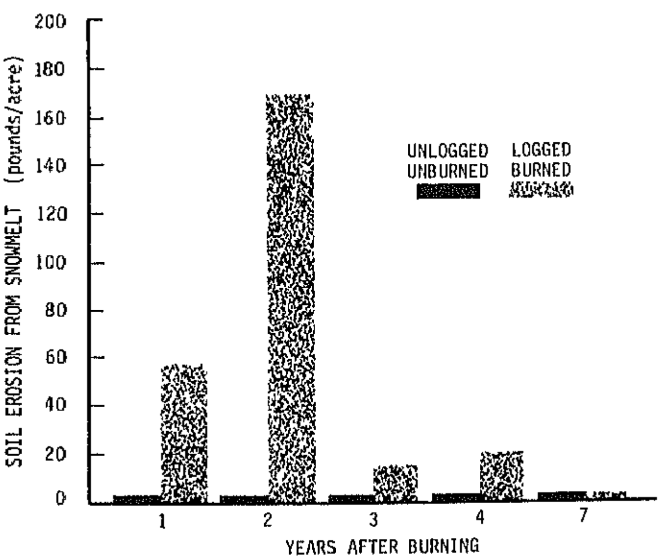

Figure 33.—Soil erosion from snowmelt overland flow for 7 years after logging and burning at Miller.

Overland flow from summer storms at Miller was much less than from snowmelt. Less than 0.2 inch (5 mm) ran off the treated plots during the first year after burning, when 12 inches (305 mm) precipitation was received. However, this small amount of overland flow produced 151 lb/acre (169 kg/ha) of sediment. Both overland flow and soil erosion declined dramatically in subsequent years (fig. 34). It is of interest to note that the largest amounts of soil erosion from summer storms and from spring runoff are almost equal—151 and 168 lb/acre (169 and 188 kg/ha), respectively. Yet, the summer storm flow (0.15 inch or 4 mm) that produced this amount of erosion was only 27 percent of the flow from snowmelt (0.55 inch or 14 mm). The more intense summer storms provide a much more efficient eroding force than does snowmelt runoff.

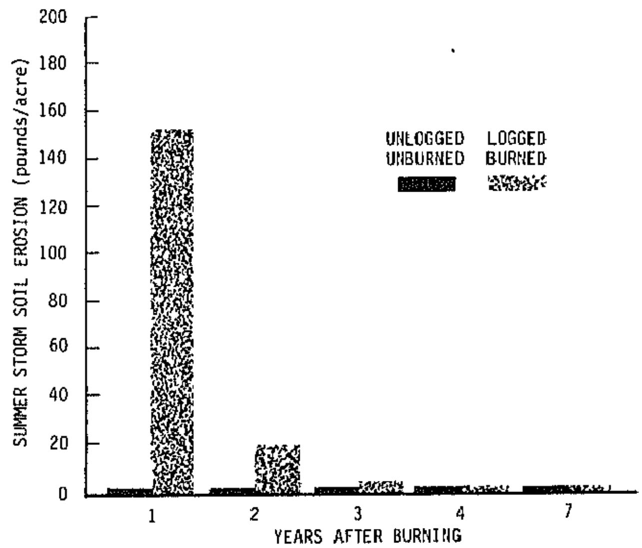

Figure 34.—Soil erosion from summer rainstorms for 7 years after logging and burning at Miller.

The records from the steeper slopes at Newman show a similar pattern. During the first 2 years after treatment less than 50 lb/acre (56 kg/ha) of soil had eroded from the burned plots as a result of snowmelt runoff. At Newman more than 10 inches (254 mm) of precipitation was recorded during the first summer after treatment and only 3 inches (76 mm) during the second summer. The overland flow resulting from this followed a similar pattern. No soil erosion was experienced from the control plots at Newman. But, during the first year after burning, erosion losses were 1,700 lb/acre (1 905 kg/ha) from the treated plots, primarily from one high-intensity summer storm. During the second year it was less than 20 lb/acre (22 kg/ha).

Nutrient Content of Runoff Water and Sediment

The organic matter content of the sediment from Miller ranged from 12 to 44 percent and that from Newman from 14 to 40 percent, much greater than the organic matter content of the surface mineral soil. The nutrients lost in this sediment at Miller declined from 11 lb/acre (12 kg/ha) during the first year to one-half lb/acre (0.6 kg/ha) during the fourth year after burning, and from 44 lb/acre (49 kg/ha) during the first year after treatment at Newman to only 1 lb/acre (1 kg/ha) the second year.

Runoff, like eroded soil, carried nutrients from the plots somewhat in proportion to its total quantity. However, the concentration of dissolved components in the runoff was especially high in the first year due to a flush of soluble materials from the ash on the burned plots

The combined losses of components measured in both water and sediment decreased rapidly from the treated plots, and approached pretreatment losses within a few years. All nutrients lost from control plots were dissolved in the runoff water, as no soil erosion was experienced. From the treated plots at Miller, 42 percent of the 28 lb/acre (31 kg/ha) loss of nutrients (total of P, K, Ca, Mg, and Na) was dissolved in the surface runoff. The dissolved portion in the losses from Newman was less, only 20 percent of the total in the 2 years of measurement, largely because of the large amount of sediment produced in the first year after treatment.

Beaufait and Packer on a runoff plot at Miller surveying the vegetation, most of which is fireweed, that developed during the 6 years following logging and broadcast burning.

Uncut forest in the stream bottom and several south-facing burned units on the background hillside at Miller. Units S-12 and -13 (those with standing dead trees in right background) and several slashed units were burned in an August 1967 wildfire

DISCUSSION AND MANAGEMENT IMPLICATIONS

Interpretation and management implications of the Miller-Newman research for each resource or discipline are presented in the same sequence as they appear in the Results section. Although interactions among the disciplines are discussed, it is not possible to quantify them. The Miller-Newman research was designed to quantify the effects of clearcutting and fire on each resource separately, not to combine resources into an analysis of variance. Hence, the interpretation of interactions among resources is subjective and somewhat speculative.

Fire Behavior and Effects

The techniques and prescriptions for use of broadcast prescribed fire in this forest type are developed to a degree that guidelines, such as those in appendix B, can be presented. Fire now may be used as a forest management tool with sufficient precision to predict and control its outcome with respect to several resources—water, soil, wildlife, vegetation development, forest regeneration, and air quality. Effects of the combined treatment (clearcutting and broadcast slash burning) have been quantified for these resources, in the Miller-Newman study. For most resources, this quantification includes fires that range the entire gamut of intensity and effectiveness. In addition, for some resources a comparison on adjacent units is made between the effects of wildfire in standing timber and clearcutting and broadcast slash burning. The methods and results of the fire phase of the Miller-Newman study were presented in detail by Beaufait and others (1977), and the management applications of this research were combined with the results of later work and presented in the Results and appendix of this paper In short—here is the tool, here is how it can be used with precision, and here are the effects on individual resources. The management implications of these effects follow.

Smoke Management

The emission products from forest fires mix with and pollute the air. This pollution is inevitable. However, with knowledgeable use of prescribed fire, the timing of that pollution, the quantity anr ratios of the pollutants emitted, and the volum and location of the polluted air are all under man' control. With these controls in mind, fire ma- agers can make use of several salient results fro the Miller-Newman study.

It has been known for some time that atmospheric conditions, particularly the height of free air convection and the velocity and direction of surface winds, influence smoke dispersion. However, in this study, fire intensity was found to have an overriding control on the height of convection columns and the elevation at which smoke plumes are dispersed. Also pointed out is the need for local weather forecasts, particularly for wind direction and velocity.

Particulates are present in the air for many miles downwind from forest fires. This particulate matter at the ground level, where people live, may be aerosols in smoke that has crept along the surface from a low-intensity fire, or it may be fallout of larger particles from a high-elevation smoke plume resulting from an intense fire. Both will be detected at air monitoring stations; but their air pollution effects are quite different. Aerosols in a smoke plume truly pollute the ground-level air with particulates and other emissions. In contrast, when fallout of larger particulates occurs, the air remains relatively clean, but the ground surface and any objects of man on that surface (automobiles, laundry on clotheslines, etc.) become dusted with ash. The study points out that ground-level downwind effects may be detected only on days with fires, not on subsequent days.

The water content of fuel controls fire intensity and the products of emission. Dry fuels and atmospheric conditions that result in a fast and intense fire produce the least particulate matter and carbon monoxide and the greatest amount of carbon dioxide for the quantity of fuel burned. Even though the total quantity of emissions from an intense fire may be less, the concentration in the smoke plume for several miles downwind from that fire may be great enough to obstruct air navigation.

Ideally, the smoke plume should be pushed upwards into an atmospheric layer not influenced by local air inversions, and thereby not likely to cause local air pollution at ground level. There the particulate aerosols and gases will move downwind at the speed and direction of upper level winds. They will remain at that level until atmospheric mixing disperses these pollutants. The particulate aerosols later will return to earth as condensation nuclei in precipitation.

Particulate matter is the primary pollutant in smoke from forest fires. The fires conducted at Miller and Newman produced approximately 30 pounds of airborne particulate per ton (15 kg/t) of fuel consumed. Management of fire intensity and timing will control the location and impact of that pollutant load.

Silviculture

Timing of prescribed fires to achieve satisfactory site preparation for silvicultural purposes is critical. Fires in spring or early summer usually burn over a wet duff layer and therefore bare little mineral soil. Following dry summers, late summer or early fall fires more effectively remove the duff layer and expose adequate mineral soil for forest regeneration. Even then, fuels and duff must dry for several days following significant precipitation. Conditions under which north slopes can be burned to substantially reduce the duff layer usually occur only in August and early September in the larch/Douglas-fir forest type. On other aspects there is more opportunity to broadcast burn logging slash and provide seedbeds.

High-intensity fires over a dry duff layer usually are unnecessary and often undesirable on mesic sites. These fires expose a high proportion of mineral soil. If a good seed crop follows, dense overstocking of tree seedlings will result. The moderate-intensity fires at Newman generated enough heat to consume most of the relatively dry duff and prepare a seedbed that was more than adequate on these mesic sites. Fires of similar intensity at Miller exposed less mineral soil because of thicker and wetter duff.

Prescribed broadcast fires in the slash at both Miller and Newman had few adverse effects on the soil and little effect on roots or rhizomes more than an inch (25 mm) beneath the surface. In contrast, dozer piling and burning on these sites no doubt would have had significant effects on the soil under the burned piles and would have killed any roots and propagules within it (Vogl and Ryder 1969).

The *Abies lasiocarpa/Clintonia* habitat type (both *Clintonia* and *Menziesia* phases) adequately regenerate if: (1) clearcuts are small (less than approximately 15 acres or 6 hectares), (2) mineral soil is exposed at an adequate number of microsites, say, on 40 percent or less of the toal area, and (3) a seed source is present along two edges. However, clearcuts meeting these criteria on steep slopes of the drier *Xerophyllum* phase still

were not adequately regenerated 5 years after burning. High surface temperatures and low soil water contents on these exposed south and west facing slopes indicate the need of shading. Randomly distributed charred debris on broadcast burned sites offers some protection for regenerating conifers. But, on these exposed slopes, the shelterwood system combined with site preparation by broadcast burning would increase the potential for adequate natural regeneration. Broadcast burning under shelterwood would require removal of subalpine fir during the first harvest, or else felling them before burning. They are usually killed by fire and, if standing, frequently will carry fire into the crowns of neighboring trees.

Timing of ripening and dispersal of conifer seed as well as its abundance must be considered when using broadcast fires as a silvicultural tool. Seed crops on upper slopes at Newman were dispersed in early to mid-October. This was 2 weeks to a month later than seed dispersal on nearby lower slopes or valley bottoms at Newman or anywhere throughout the Miller area. Prescribed fires can, therefore, be accomplished on upper slopes through early October before seed is dispersed. Elsewhere the dispersed seed will be destroyed by fires later than about mid-September. Burning after that time may be acceptable during years without satisfactory seed crops, but would be ill advised in a year with a bumper seed crop.

At Newman, the central portion of some clearcuts was seeded by a high proportion of "light-seeded" tree species, such as larch. If a high proportion of "heavy-seeded" species is desired, such as ponderosa pine, the manager should either decrease clearcut size to correspond to seed dispersal limits of desired species or plant the central portion of large clearcuts. Natural dispersal may not provide sufficient seed on dry sites beyond 300 feet (90 m) from the timber edge even in good seed years. For example, the mesic *Thuja/Clintonia* (*Menziesia* phase) habitat type regenerated adequately with half as much seed as fell on *Pseudotsuga/Vaccinium globulare* (*Xerophyllum* phase) habitat type, where regeneration was grossly inadequate.

Germination and seedling survival are better on seedbeds with little or no duff. All species germinated in greater numbers on seedbeds with 0 to one-half inch (0-13 mm) of duff than on those with a thicker duff layer. Engelmann spruce benefited most and Douglas-fir least from exposure of mineral soil. Both germination and seedling survival were more adversely affected by a thick residual duff layer on the steep slopes and drier conditions at Newman than on the more moderate slopes at Miller. Apparently the duff layer must be essentially removed from any microsite on which natural conifer regeneration is expected in the larch/Douglas-fir type. How much of the overall area needs to be bared to mineral soil is a question that can be answered only on a site-by-site basis, taking into account the expected seed crops and all mortality between the time of seed dispersal and satisfactory seedling establishment.

Natural regeneration potential varies significantly by habitat type. Clearcuts on only three of the eight habitat types on the study areas regenerated adequately, with at least 1,000 seedlings per acre (approximately 2,500 per hectare) and with 50 percent of the milacre plots stocked (table 12). Clearcuts on three other types need supplemental planting or seeding to restock them adequately. The regeneration potential of the two Douglas-fir habitat types is marginal at best.

Because most prescribed fires exposed considerable mineral soil on all slopes at both Miller and Newman, direct seeding of larch, spruce, and true firs may be acceptable on all habitat types except those with a poor potential for natural regeneration. Sowing enough seed to assure adequate regeneration on these harsher sites would be impractical because of limited and costly seed supplies. Planting is the only alternative for these sites. Planting was successful for all tested tree species in the *Abies lasiocarpa/Clintonia* habitat type (all phases) at Miller. At Newman, however, planting success for all species other than ponderosa pine varied by habitat type (table 13).

Vegetative Development

Vegetational changes following the treatments at Miller and Newman serve as an ecological baseline, providing a frame of reference so the manager may evaluate and predict the effects of clearcutting and broadcast burning or of wildfire on the plant community. Perhaps the most important general concept for managerial application is a focus of attention beyond the slash reduction aspect of prescribed fire to its effect on the duff layer and the surface mineral soil. It is here that a burning treatment most greatly affects preburn vegetation, seed stored in the soil, and the seedbed for introduced seed.

HERB STAGE OF SUCCESSION

The herb stage usually initiates forest succession. The period of growth for herbs to reach maturity is shorter than that for woody plants. Thus, at the beginning of succession, if herbs, shrubs, and trees all become established in the first year, as they often do, herbs will dominate the initial stage because they grow and develop most rapidly. By definition, herbs annually die back to the ground. With this growth pattern, there often are sudden changes in cover from year to year caused by changing climate conditions. Once initial growth to mature size is complete, further increase in herb cover results from increasing (expanding) populations. Both processes often operate concurrently.

The duration of the herb stage is determined by development rates of predominant species in the next stage. An herb stage 9 or more years old indicates absence or slow development of shrub or tree species. Any particular stage of succession seldom shuts itself down, rather it is replaced by development of another, more dominant, life form. Therefore, those areas with short herb stages had rapidly developing shrub components.

Table 12.—Expected natural regeneration potential by habitat type

Habitat type	Seedling density	Stocking	Natural regeneration potential
	Trees/acre	*Percent*	
Abies lasiocarpa/Clintonia (*Menziesia* phase)	2,916	76	Good
Thuja/Clintonia (*Menziesia* phase)	2,076	70	Good
Abies lasiocarpa/Clintonia (*Clintonia* phase)	3,160	60	Good
Abies grandis/Clintonia	960	43	Fair
Abies lasiocarpa/Clintonia (*Xerophyllum* phase)	1,796	32	Fair
Abies grandis/Xerophyllum	331	18	Poor
Pseudotsuga/Physocarpus	438	12	Poor
Pseudotsuga/Vaccinium globulare (*Xerophyllum* phase)	108	6	Poor

Table 13.—Expected survival for planted conifers by habitat type on Newman Ridge

Habitat type	Expected species survival		
	Highest	Moderate	Lowest
Abies grandis/Clintonia	—	Lodgepole pine Douglas-fir Western larch Grand fir	—
Abies grandis/Xerophyllum	Ponderosa pine	Douglas-fir Western larch Lodgepole pine Grand fir	—
Pseudotsuga/Physocarpus	Ponderosa pine	—	Western larch Douglas-fir Lodgepole pine
Pseudotsuga/Vaccinium globulare	Ponderosa pine	Douglas-fir Western larch Lodgepole pine	—
Thuja/Clintonia	Western larch Douglas-fir Lodgepole pine Grand fir	—	—

This pattern may result from either a high survival of preburn resident shrubs or the presence of rapidly growing pioneer shrubs. Most rapid shrub development usually results from a combination of these two processes, as on several units at Newman.

FIRE EFFECTIVENESS

The influence of fire on undergrowth and juvenile overstory plants is centered at the mineral soil-duff surface. The more heat applied here, the greater is mortality of resident plant species, and the greater is the opportunity for site occupancy by invading pioneers. Conversely, the less heat applied to this point, the higher the survival of resident plants and the less suited is the site for pioneer species. The key to changing abundance and composition of vegetation lies in controlling fire intensity, or more specifically, in controlling the amount of heat applied to the mineral soil-duff surface. In this study, those units with the driest lower duff at the time of burning produced postburn site conditions most favorable to pioneer species.

Many very desirable timber species and shrubs that supply excellent wildlife habitat are pioneers. On Miller and Newman these include western larch, lodgepole pine, snowbrush ceanothus, and Scouler willow. Of the 14 units sampled at Miller, those burned by wildfire had the greatest development of pioneer shrubs as well as an abundance of tree seedlings. At Newman a similar response was noted where hot prescribed fires emulated the Miller wildfire; however, the pioneer tree component here was not as abundantly represented. Clearcutting at Newman removed both the on-site seed source and the temporal shade for ameliorating the environment of tree seedlings.

Unit S-13 at Miller provides a classic example of how the mesic conifer forest in the Northern Rocky Mountains responds to disturbance by wildfire. All major components of the seral vegetation are developing on this unit in an environment that must closely approximate that under which the former forest stand evolved. The composition of the plant community resulting from this intense fire, during which most of the duff was burned, when compared with that resulting from a less effective fire on S-1 at Miller, is evidence that both silvicultural and big-game habitat values can be enhanced by effective burning.

Effective fires remove or markedly reduce resident plant species and make the site more favorable for immigrant or pioneer species. Thus the potential for manipulating changes in vegetation is greatest following intense and effective fires. Conversely, low effective burning treatment somewhat reduces resident species, but not enough to prevent their rapid recovery and return to their earlier level of competition. For example, on many sites at Miller or Newman, if snowbrush ceanothus is the favored species, an intense and effective fire should be prescribed; whereas, if blue huckleberry is the favored species, a less effective fire would be in order.

Small Mammals

Seed-eating rodents are common, making up 70 to 98 percent of the small mammal community in the forest environment. In some years these rodents are much more abundant than in others. Deer mice, especially, follow a consistent pattern of increasing markedly during the year following a heavy conifer seed crop.

Even an intense, deep-burning fire will not eliminate rodents, but it does sharply reduce the diversity of small mammal species, essentially leaving deer mice as survivors. Deer mice appear to survive even an intense fire in good numbers; then their populations rapidly increase through reproduction and through invasion of the burned area. A fire, in which understory vegetation is mainly altered in degrees rather than kind, can sharply reduce small mammal populations for a year following treatment. By then exceptionally good habitat for rodents has developed and sustained high populations of several species are maintained on the lightly burned site for 4 or more years. Such a fire may temporarily offer the least hazard to tree seeds and seedlings from rodents because of the buffering effect of other abundant food combined with relatively low populations of seed-eating rodents.

Rodent populations generally are favored by clearcutting and broadcast burning. These increased populations, being made up of primarily conifer seed-eaters, can measurably reduce tree regeneration from seed. Especially on clean burns, direct seeding should not be attempted without taking rodent control measures because of high deer mouse populations for at least 4 postburn years. By then planting may be the only reasonable alternative.

Small mammals, like many familiar wildlife species, reach their annual maximum numbers a

the end of each growing season, when food and cover are most abundant. They are least numerous in the spring, after the winter stress period. Therefore, direct seeding of conifers is best done in the spring, especially if there has been a heavy seed crop the previous year, prior to annual recruitment in the rodent population. Thus, seeds may germinate and seedlings develop before the rodent population peaks.

Soils and Watershed

The soils and watershed data were taken from undisturbed forest and from sites that had been clearcut and broadcast burned. Some soils data also came from the Miller wildfire area. These are the treatments to which these results may be applied. The runoff and erosion data definitely do not apply to roads, trails, and other drastically disturbed sites, even though these sites usually undergo the most accelerated erosion and produce most of the sediment associated with logging operations.

Burning of logging debris in this northern coniferous forest, if broadcast over the clearcut area, should not induce sufficient water repellency into these medium- to fine-textured soils to be of any concern to land managers. Nor should the small reduction in organic matter in the surface mineral soil be cause for worry. Changes in the surface organic horizon, however, particularly its complete consumption by intense fires, may be of significance. This surface organic layer protects the soil from direct raindrop impact. Loss of this organic layer on steep slopes, such as at Newman, may result in severe erosion if intense summer storms are received.

Clearcutting and broadcast burning effected some measurable changes in soil chemistry and nutrient availability. Nutrient cycling was interrupted, the soil environment was altered, and a layer of debris and ash was deposited on the surface. Burning volatilized about a third of the nitrogen in the surface organic horizon. Leaching and erosion of the ash-duff layer during the next 2 years markedly reduced the nutrient content of this horizon. At least part of this loss can be accounted for by an increased available nutrient content in the underlying mineral soil. Mineral soil pH also increased. These relatively fine-textured soils probably trapped within the rooting zone most of the nutrients released by cutting and burning. Nitrogen lost through volatilization is great, but most of this is part of the total nitrogen supply. Total nitrogen is no measure of nitrogen actually available for plant growth. Available nitrogen supplies were not assessed.

Rapid recovery of vegetation on these sites has reestablished nutrient cycling and has again protected the soil surface. None of the nutrient changes measured should adversely alter site quality.

The relatively small amounts of soil erosion measured on these plots should be comforting to managers contemplating similar treatment on similar soils and slopes. The maximum amount of eroded material produced from each acre at Miller during the first year after treatment was only a few hundred pounds. This amount of sediment easily can be kept from streams with the use of undisturbed buffer strips. An example of more severe erosion from summer storms occurred on the steeper slopes at Newman with the chance occurrence of an intense storm during the first summer. However, even here, erosion from the logged-burned plots cannot be considered severe even by conservative agricultural standards.

Impairment of watershed protection and attendant increases in runoff and erosion are quite similar on both areas. With the exception of southerly aspects, the impact is acceptable. Southerly aspects are driest, they were impacted with the most intense burns, and they exhibited the most adverse effects to soil and vegetative characteristics as a result of treatment. Most importantly, these south slopes recovered least during the 7 years following burning.

With reasonable precautions, site quality and aquatic habitat will not be adversely impacted from clearcutting and broadcast burning on these or similar sites. The precautions are those that apply anywhere in mountainous terrain—to minimize mineral soil exposure and disturbance, especially through construction of roads, skid trails, and firebreaks. A further recommendation would be to minimize disturbance on south-facing slopes. These recovered slowly and were thus exposed for an unacceptably long period to overland flow and erosion. Perhaps a shelterwood system would be more appropriate on south slopes.

Interactions

Quantitative data available from this research deal almost exclusively with effects of clearcutting

and fire on discrete resources or disciplines. It is well known, however, that these entities interact. Research design, unfortunately, does not permit a quantitative analysis of second-level interactions that followed clearcutting and fire. Therefore the remainder of this discussion is qualitative; it describes some observations made on the Miller and Newman areas during the course of this study and their possible implications.

SMOKE MANAGEMENT AND THE SOIL AND WATER RESOURCE

Some plant nutrients are volatilized in fires and some are carried away as particulate matter in the smoke. Those lost through volatilization are, for all intents and purposes, permanently added to the atmosphere. But those carried aloft as 30 pounds of particulate matter per ton of fuel consumed are returned to the earth's surface. This return occurs as fallout of flyash for several miles downwind from the fire, as physical trapping of smoke particulates in vegetation downwind from the fire (especially applicable to low-intensity fires without a convection column), and as precipitation, with the fine particulates being nuclei for the formation of water droplets.

The concentration of nutrients in precipitation falling through smoke plumes from forest fires may be 20 to 70 times greater than normal (Clayton 1976). DeByle and Packer (1972) noted an unexplained increase in the nutrient content of overland flow from control plots in the forested areas at Miller in 1967, when the greatest acreage was burned. Trapping of dry airborne ash by the uncut forest, and return of particulate matter in precipitation may have accounted for this increased nutrient content. This transfer of plant nutrients in forest fire smoke is statistically significant but apparently of little ecological importance (Clayton 1976). It should be noted, though, that the nutrients lost in smoke particulates from burned sites become nutrient additions at downwind locations. The direction, distance, and dilution of this downwind aerial fertilization can be partially controlled from prescribed fires.

SILVICULTURE AND VEGETATIVE DEVELOPMENT

Growth of vegetation after clearcutting and broadcast slash burning and the successional changes in this vegetation affect establishment and growth of conifer seedlings. As pointed out earlier, intense fires reduced competing vegetation to a minimum, set back plant succession furthest, and provided the most exposure of mineral soil as seedbed. But protection and shading of the site are also reduced to a minimum by intense fires. Most of these sites are quickly occupied with herbaceous vegetation, particularly fireweed, and shading for the newly established conifer seedlings is provided. The shade of living vegetation may favorably alter the microclimate for conifer seedlings; but as this vegetation develops, it also competes with relatively slow-growing conifer seedlings for light, nutrients, and water. Data are not available from Miller or Newman at this stage of vegetational development to assess the degree of competition between seedlings and other vegetation. Nor are there data available to quantify the effects of shade from this vegetation on the survival and growth of conifer seedlings. When both pioneer shrubs and trees become established in the first year, as on Miller S-12 and S-13, the effects of shrubs on tree seedlings would be less than if there is a delay in tree establishment.

Low-intensity fires that do not remove the duff layer not only do not provide an adequate seedbed for conifers, but those seedlings that develop on these sites grow more slowly than on intensely burned areas. This, in part, may be due to less competition from other vegetation on intensely burned sites. On sites with low-intensity and less effective fires, new conifer seedlings must compete with already established vegetation.

SILVICULTURE AND SMALL MAMMALS

The interactions between seed-eating rodents and seed and seedling survival of conifers are explained under Small Mammal Populations in the Results and Discussion sections. An additional but speculative point deserves attention. A fire that kills all aboveground vegetation and bares the mineral soil, initially reduces the rodent population but, shortly afterward, provides an ideal habitat for a large increase in deer mice, primarily seed-eaters. The same physical conditions provide the best conifer seedbed. In contrast, a less effective fire does not deplete the rodent population nor its food supply as much, does not cause as marked an increase in seed-eating rodent numbers, and, as a result, there should be less impact on conifer seed and seedlings by these rodents It would appear that more conifer seeds would survive on these burns to allow stocking of those few microsites that were properly prepared, namely burned to mineral soil. If true, this is evidence for a natural balance having evolved between fire intensity, rodent populations, and conifer seedling establishment.

SILVICULTURE AND THE SOIL AND WATER RESOURCE

As stated earlier, conifer seedlings growing on burned areas were more vigorous than those on unburned sites. This increased vigor may be due to less competition from other vegetation (already speculated) or be due to a more favorable chemical and physical environment. The ash, as shown in the soils results, adds a small amount of available plant nutrients to the surface mineral soil. Also, the blackened and exposed surface results in an altered microclimate, both above and within the soil, that may be more favorable to conifer seedling growth.

Drought was the leading cause of seedling death on south slopes and the second leading cause on all others Careful management may reduce this mortality. In part the soil moisture regimen can be influenced by management. Shade from dead vegetation not only will prevent lethal temperatures at the soil-air interface, but also will reduce evaporation from the surface soil, the critical layer for newly established seedlings. However, live vegetation competing with the conifer seedlings usually transpires more water than its shade conserves. When extrapolating these results to other locations, it must be kept in mind that fine-textured soils, such as the clays and loams at Miller and Newman, contain a greater amount of available water for plant growth than coarse-textured soils. For this reason, a south-facing slope with coarse sandy soil that has been denuded of all vegetation, both live and dead, will be an especially harsh environment for conifer seedling survival during dry summers, such as that experienced in 1967.

The silviculturist who wants bare soil exposed for the best conifer seedbed and the watershed manager who desires a layer of vegetation and duff to protect the mineral soil from raindrop impact and overland flow seem to have conflicting goals. These opposing objectives are more apparent than real. The bare soil openings necessary for satisfactory forest regeneration need not be large nor extensive enough to cause undue accelerated erosion. Through the use of broadcast prescribed burning, it is possible to reduce plant competition, expose sufficient mineral soil microsites for tree seedling establishment, and still maintain satisfactory mineral soil cover to control erosion from all but the most intense storms. The silviculturist and watershed manager are really in agreement on what is needed—partial exposure of mineral soil to permit sufficient but not too much natural forest regeneration, and sufficient protection of the site with dead vegetation. This agreement is particularly obvious in the recommendations given for south exposure at both Miller and Newman, where a shelterwood system is probably best from both points of view.

SILVICULTURE AND ESTHETICS AND WILDLIFE

This study and others have shown that natural regeneration of most conifer species on small clearcuts is more uniform and abundant than on large clearcuts. Seed dispersal of most conifers is not sufficient to adequately regenerate sites more than 100 yards (approximately 100 m) from the uncut forest. Again, good silviculture and other forest uses are in agreement. Small clearcuts are less of an esthetic impact than large ones. Small clearcuts also offer the maximum edge and greatest diversity of habitats for wildlife. Wild ungulates will use the entire area of small clearcuts for browsing as opposed to primarily the periphery of large openings.

If carefully done, broadcast burning will bare the desired amount of mineral soil for forest regeneration. Frequently, too much is bared with dozer piling of slash. Also, broadcast burning leaves a relatively uniform distribution of shade from logs and dead vegetation. Dozer piling of slash removes this shade. Broadcast burning has much less esthetic impact than other debris disposal techniques. Within a few years after treatment the broadcast burned site, with its uniform distribution of coarse debris, appears much more natural than the remains of piled or windrowed debris from other conventional slash disposal methods.

In recent years there has been increased emphasis on maintenance of avian habitats in the managed forest, especially habitat for cavity nesters and raptors. This was not a part of the Miller-Newman research. Hence, all trees were felled on all of the clearcuts. However, there was no pressing reason that this had to be done. Some trees could have remained. To maintain cavity nesting and feeding sites as well as raptor perches, as many large cull trees and snags as possible should be left standing (McClelland and others 1979). Ideally, culls ought to be killed in the prescribed fire to prevent their competing with the next crop of trees, to prevent their providing perhaps genetically inferior seed, and to control any insects or diseases present in them. To insure these culls are girdled with

sufficient heat, slash fuel should be concentrated about their bases. Because they may "crown out," these trees must be away from the periphery of clearcuts, so control of the prescribed fire would not be jeopardized These dead trees may benefit the developing forest under them—by providing shade, by providing nesting habitat for insectivorous birds, and by providing perches for raptors that prey on seed-eating rodents On the other hand, on sites where lightning strikes are common, these snags may create an unacceptable fire hazard that could threaten the surrounding young forest.

VEGETATIVE DEVELOPMENT AND SMALL MAMMAL POPULATIONS

This research has shown that size and the diversity of rodent populations are related to cover, size, and species diversity of vegetation. At Newman this was especially evident on the contrasting lightly burned north and intensely burned south slopes. Possible influences of vegetation on these mammal populations have been discussed. The converse, the effect of small mammals on the developing vegetation, remains unknown. With the exception of conifer seedling establishment and development, there has been no attempt in this research to quantify this effect. For example, we do not know what role rodents play in distributing seeds of shrubs, or in establishing forbs or shrubs in this environment.

VEGETATIVE DEVELOPMENT AND THE SOIL AND WATER RESOURCE

Especially where fireweed was an important component of the postburn vegetation, herbaceous growth flourished during the first 2 or 3 postburn years. Was this flush, which often seemed to decline without cause, due to fertilization of these sites by ash? Was it due to microclimate alteration? Or was it due to the ecophysiology of the plant species involved? Perhaps it is a combination of all three. Fertilization was present, but seemed trivial. Both the above- and belowground microclimate was altered by clearcutting and fire; and it is well known that the principal species, fireweed, dominates many northern coniferous sites after burning and, therefore, must be especially adapted to these conditions. As is so frequently the case in research—one question is answered (fireweed increases markedly, then for no apparent reason declines) only to raise a more fundamental question—why?

Plant cover data were taken on control plots and on clearcut and burned plots for several years to help explain the amount of runoff and erosion experienced. These data were gathered with a much different technique (a point analyzer that resulted in precise measurements of cover at or very near the soil surface on small transects) than the cover measurements taken for assessing vegetative development (estimates of cover on larger transects from a reference point farther above the ground). Also, the units and transects used for quantifying vegetative development were not the same as the units and locations of the runoff plots. Despite these differences, the data from runoff plots and vegetative development transects that have been subjected to similar treatments and conditions show similar trends. Differences noted often are due to location; for example, none of the runoff plots were situated where dense growth of ceanothus occurred after burning, whereas some of the vegetation development transects were in dense ceanothus patches.

The usual cycling of nutrients in the northern coniferous forest is interrupted by the treatments applied at Miller and Newman. During the first postburn year uptake of nutrients by plants is minimal. How soon the cycling of nutrients into developing vegetation, and their return each year as litter, reaches a level similar to that of the preharvest forest was not determined. Perhaps in this forest type this is reached when deeply rooted shrubs and young trees again fully occupy the site. This on the average probably would be 10 to 20 years after harvesting and broadcast burning at Miller and Newman.

Soil microclimate, soil pH, and the amount and chemical nature of available nitrogen are all affected by the amount and the species composition of vegetation developing after treatment. Available nitrates should be more abundant and soil pH higher in the early stages of herbaceous and pioneer shrub cover than after the sites again become dominated by coniferous forest. Microclimate is markedly altered by clearcutting and burning, then begins a gradual return to pretreatment conditions as vegetation and the organic soil horizon develop. Because none of these effects have been actually measured in the Miller-Newman research, we can only speculate on the magnitude and direction of these nutrient and microclimate changes.

PUBLICATIONS CITED

ams, Donald F., Robert K. Koppe, and Elmer binson.

1976. Air and surface measurements of constituents of prescribed forest slash smoke. *In* Proc Int. Symp.: Air Quality and Smoke from Urban and Forest Fires [Fort Collins, Colo., Oct 1973]. p. 105-147. Natl Acad. Sci., Washington, D.C.

lgren, I F, and C. E. Ahlgren.

960. Ecological effects of forest fires Bot Rev. 26(4):483-533

aufait, William R

960. Some effects of high temperatures on the cones and seeds of jack pine. For. Sci. 6(3).194-199.

aufait, William R.

962. Procedures in prescribed burning for jack pine regeneration. Mich. Coll. Mining and Tech., Tech. Bull. 9, 39 p.

aufait, William R.

966a An integrating device for evaluating prescribed fires. For. Sci. 12(1):27-29.

aufait, William R.

966b. Prescribed fire planning in the intermountain West. USDA For Serv Res. Pap. INT-26, 27 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

aufait, William R.

971. Fire and smoke in Montana forests. *In* Forest land use and the environment. 23 p. Richard E. Weddle, ed. Univ. Mont., Missoula.

aufait, William R., Charles E. Hardy, and William Fischer.

977. Broadcast burning in larch-fir clearcuts: the Miller Creek-Newman Ridge study. USDA For. Serv. Res. Pap. INT-175, rev., 53 p. Intermt. For and Range Exp. Stn., Ogden, Utah.

aufait, William R., Michael A. Marsden, and dney A. Norum.

974. Inventory of slash fuels using 3P subsampling. USDA For. Serv. Gen. Tech. Rep. INT-13, 17 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

wn, James K.

974. Handbook for inventorying downed woody material. USDA For. Serv. Gen. Tech. Rep. INT-16, 24 p, Intermt. For. and Range Exp. Stn., Ogden, Utah.

kman, R. E.

962. Two prescribed summer fires reduce abundance and vigor of hazel brush regrowth. USDA For. Serv., Lake States For. Exp. Stn. Tech. Note 620, 2 p.

Buckman, R. E.

1964. Effects of prescribed burning on hazel in Minnesota. Ecology 45(3):626-629.

Byram, George M.

1959. Combustion of forest fuels, *and* Forest fire behavior, chap. 3 and 4. *In* Forest fire: control and use. p. 61-123. McGraw-Hill Book Co., New York.

Charlson, Robert J.

1968. Atmospheric aerosol research at the University of Washington. Air Pollution Contr. Assoc J 18:652-654.

Clayton, James L.

1976. Nutrient gains to adjacent ecosystems during a forest fire: an evaluation. For. Sci 22(2):162-166.

DeByle, Norbert V.

1976. Soil fertility as affected by broadcast burning following clearcutting in Northern Rocky Mountain larch/fir forest. *In* Proc. Tall Timbers Fire Ecol. Conf. 14:447-464. [Missoula, Mont., Oct. 1974.]

DeByle, Norbert V., and Paul E. Packer.

1972. Plant nutrient and soil losses in overland flow from burned forest clearcuts. *In* Watersheds in transition, Am. Water Resour. Assoc. Symp. Proc. p 296-307.

Fahnestock, George R.

1960. Logging slash flammability. USDA For. Serv., Intermt. For. and Range Exp. Stn., Res. Pap. 58, 67 p. Ogden, Utah.

Fahnestock, George R., and John H. Dieterich.

1962. Logging slash flammability after 5 years. USDA For. Serv., Intermt. For. and Range Exp. Stn., Res. Pap. 70, 15 p. Ogden, Utah.

Fischer, William C.

1978. Planning and evaluating prescribed fires —a standard procedure. USDA For. Serv. Gen. Tech. Rep. INT-43, 19 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Fryxell, Roald.

1965. Mazama and Glacier Peak volcanic ash layers: relative ages. Science 147(3663): 1288-1290.

Garrison, G. A., J. M. Skovlin, C. E. Poulton, and A. H. Winward.

1976. Northwest plant names and symbols for ecosystem inventory and analysis. 4th ed. USDA For. Serv. Gen. Tech. Rep. PNW-46, 263 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

Gashwiler, Jay S.

1966. Tree seed abundance vs. deer mouse populations in Douglas-fir clearcuts. *In* Proc. Soc. Am. For., 1965, p. 219-222. Washington, D.C.

Gashwiler, Jay S.
1970. Plant and mammal changes on a clear-cut in west-central Oregon. Ecology 51(6): 1018-1926.

Getz, Lowell L.
1968. Influence of water balance and micro-climate on the local distribution of the red-back vole and white-footed mouse. Ecology 49(2):276-286.

Gunderson, Harvey L.
1959. Red-backed vole habitat studies in central Minnesota. J. Mammal. 40(3):405-412.

Habeck, James R., and Robert W. Mutch.
1973. Fire-dependent forests in the northern Rocky Mountains. J. Quat. Res. 3(3):408-424.

Hare, Robert C.
1965. Chemical test for fire damage. J. For. 63(12):939.

Hitchcock, C. Leo, and Arthur Cronquist.
1973. Flora of the Pacific Northwest. 730 p. Univ. Wash. Press, Seattle.

Hooven, Edward F.
1976. Changes in small mammal populations related to abundance of Douglas-fir seed. Oreg. State Univ., Corvallis, School For., Res. Note 57, 2 p.

Howard, W.E., R. L. Fenner, and H. E. Childs, Jr.
1959. Wildlife survival in brush burns. J Range Manage. 12(5):230-234.

Jameson, E. W., Jr.
1953. Reproduction of deer mice (*Peromyscus maniculatus* and *P. boylei*) in the Sierra Nevada, California. J. Mammal. 34(1):44-58.

Jensen, Chester E.
1973. Matchacurve-3: multiple-component and multi-dimensional mathematical models for natural resource studies. USDA For. Serv. Res. Pap. INT-146, 42 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Jones, J. Knox, Jr., Dilford C. Carter, and Hugh H. Genoways.
1975. Revised checklist of North American mammals north of Mexico. Texas Tech. Univ. Mus. Occas. Pap. No. 28, 14 p.

Lawrence, George E.
1966. Ecology of vertebrate animals in relation to chaparral fire in the Sierra Nevada foothills. Ecology 47(2):278-291.

LeBarron, Russell K.
1957. Silvicultural possibilities of fire in northeastern Washington. J. For. 55(9):627-630.

Little, Elbert L., Jr.
1953. Checklist of native and naturalized trees of the United States (including Alaska). U.S. Dep. Agric., Agric. Handb. 41, 472 p.

Malte, P. C
1975. Pollutant production from forest slash burns Wash. State Univ., Coll Eng. Bull. 339, 32 p.

Maser, Chris, and Robert M. Storm.
1970. A key to microtinae of the Pacific Northwest (Oregon, Washington, Idaho). 162 p. O. S. U. Book Stores, Inc., Corvallis, Oreg.

Maser, Chris, James M. Trappe, and Ronald A. Nussbaum.
1978. Fungal-small mammal interrelationships with emphasis on Oregon coniferous forests. Ecology 59(4).799-809

McClelland, B. Riley, Sidney S. Frissell, William C. Fischer, and Curtis H. Halvorson.
1979. Habitat management for hole-nesting birds in forests of western larch and Douglas-fir. J. For. 77(8)·480-483

Miller, Melanie.
1977. Response of blue huckleberry to prescribed fires in a western Montana larch-fir forest. USDA For Serv. Res. Pap. INT-188, 33 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Norum, Rodney A.
1974. Smoke column height related to fire intensity. USDA For. Serv. Res. Pap. INT-157, 7 p. Intermt. For. and Range Exp Stn., Ogden, Utah

Norum, Rodney A.
1977 Preliminary guidelines for prescribed burning under standing timber in western larch/Douglas-fir forests. USDA For. Serv. Res. Note INT-229, 15 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Odum, Eugene P.
1944. Water consumption of certain mice in relation to habitat selection. J. Mammal. 25(4):404-405.

Olson, D. S., and G. R. Fahnestock.
1955. Logging slash—a study of the problem in Inland Empire forests. Univ. Idaho For. Wildl. and Range Exp. Stn. Bull. 1, 48 p.

Packer, Paul E
1959. Watershed management problems in the northern Rocky Mountain region. USDA For. Serv., Intermt. For. and Range Exp. Stn., Res. Pap. 57, 28 p. Ogden, Utah

Packer, Paul E., and Bryan D. Williams.
1976. Logging and prescribed burning effects on the hydrologic and soil stability behavior of larch/Douglas-fir forests in the Northern Rocky Mountains. *In* Proc. Tall Timbers Fire Ecol. Conf. 14:465-472. [Missoula, Mont., Oct. 1974].

Pfister, Robert D., Bernard L. Kovalchik, Stephen F. Arno, and Richard C. Presby.
1977. Forest habitat types of Montana USDA For. Serv Gen. Tech. Rep. INT-34, 174 p. Intermt. For. and Range Exp. Stn., Ogden, Utah

Radvanyi, Andrew.
1973. Seed losses to small mammals and birds *In* Direct Seeding Symposium [Ottawa, Can., 1973]. p. 67-75. Dep. Environ., Can. For. Serv. Publ. No. 1339.

Roe, Arthur L., William R. Beaufait, L. Jack Lyon, and Jerry L Oltman.
1971. Fire and forestry in the northern Rocky Mountains—a task force report. J. For. 68(8):464-470.

Rothermel, Richard C., and Hal E Anderson.
1966. Fire spread characteristics determined in the laboratory USDA For. Serv. Res. Pap. INT-30, 34 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Shearer, Raymond C.
1975 Seedbed characteristics in western larch forests after prescribed burning. USDA For Serv. Res. Pap INT-167, 26 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Shearer, Raymond C.
1976 Early establishment of conifers following prescribed broadcast burning in western larch/Douglas-fir forests. *In* Proc. Tall Timbers Fire Ecol. Conf. 14:481-500. [Missoula, Mont, Oct 1974]

Society of American Foresters.
1954 Forest cover types of North America. 67 p. Soc. Am For., Washington, D.C.

Steele, Robert W.
1964. Effects of prescribed burning on forest duff depth. West. For. and Conserv Assoc. Annu. Meet Proc. 1964:20-21.

Steele, Robert W., and William R. Beaufait.
1969. Spring and autumn broadcast burning of interior Douglas-fir slash Mont. For. and Conserv Exp. Stn. Bull. 36, 12 p.

Stickel, Lucille F.
1954. A comparison of certain methods of measuring ranges of small mammals J. Mammal. 35(1):1-15.

Tevis, Lloyd, Jr.
1956 Effect of a slash burn on forest mice. J Wildl. Manage 20(4):405-409.

Thomas, P. H.
1958. On the rate of burning of cribs of wood Joint Fire Res. Organ., Boreham Wood, Herts, England. Fire Res. Note 370

Thomas, P. H.
1963. The size of flames from natural fires. *In* Ninth Int. Symp. Combust. p 844-859. Academic Press, New York.

USDA Forest Service.
1964. National fire-danger rating handbook. USDA For. Serv. Handb. 5109.11.

USDA Forest Service.
1974. Seeds of woody plants in the United States. USDA For. Serv. Handb. 450, 883 p.

U.S. Department of Health, Education and Welfare.
1969. Air quality criteria for particulate matter. Natl. Air. Pollut. Contr. Admin. Publ. AP-49, 211 p. Washington, D.C.

Van Wagner, C. E.
1965. Prescribed burning experiments, red and white pine. Can. Dep. For. Publ. 1020, 27 p.

Vogl, Richard J., and Calvin Ryder.
1969. Effects of slash burning on conifer reproduction in Montana's Mission Range. Northwest Sci. 43(3):135-147.

Wellner, Charles A.
1970. Fire history in the northern Rocky Mountains. *In* The Role of Fire in the Intermountain West Symp. [Missoula, Mont., Oct. 1970]. p. 42-64. Intermt. Fire Res. Counc. Proc.

Wikstrom, J. H., and J. R. Alley.
1967. Cost control in timber growing on the National Forests of the Northern Region. USDA For. Serv. Res. Pap. INT-42, 37 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Williams, Olwen.
1955. Distribution of mice and shrews in a Colorado montane forest J. Mammal. 36(2):221-231.

APPENDIX A

COMMON AND SCIENTIFIC NAMES OF SPECIES

(Little 1953; Hitchcock and Cronquist 1973; Jones and others 1975; Garrison and others 1976; and Pfister and others 1977.)

Animals

Clethrionomys gapperi	southern red-backed vole
Eutamias ruficaudus	red-tailed chipmunk
Glaucomys sabrinus	northern flying squirrel
Lepus americanus	snowshoe hare
Microtus longicaudus	long-tailed vole
Mustela erminea	ermine
Neotoma cinerea	bushy-tailed woodrat
Peromyscus maniculatus	deer mouse
Sorex vagrans	vagrant shrew
Tamiasciurus hudsonicus	red squirrel

Plants

Trees

Abies grandis (Dougl.) Lindl.	grand fir
Abies lasiocarpa (Hook.) Nutt.	subalpine fir
Larix occidentalis Nutt.	western larch
Picea engelmannii Parry	Engelmann spruce
Pinus contorta Dougl.	lodgepole pine
Pinus monticola Dougl.	western white pine
Pinus ponderosa Laws.	ponderosa pine
Pseudotsuga menziesii (Mirb.) Franco	Douglas-fir
Thuja plicata Donn	western redcedar

Shrubs

Acer glabrum Torr.	Rocky Mountain maple
Ceanothus velutinus Dougl.	snowbrush ceanothus
Lennaea borealis L.	longtube twinflower
Menziesia ferruginea Smith	rusty menziesia
Physocarpus malvaceus (Greene) Kuntze	mallow ninebark
Rubus parviflorus Nutt.	western thimbleberry
Salix scouleriana Barratt	Scouler willow
Spiraea betulifolia Pall.	birchleaf spirea
Taxus brevifolia Nutt.	Pacific yew
Vaccinium globulare Rydb.	blue huckleberry

Herbs and Grasses

Arnica latifolia Bong.	broadleaf arnica
Calamagrostis rubescens Buckl.	pinegrass
Carex concinnoides Mack.	northwestern sedge
Clintonia uniflora (Schult.) Kunth	queencup beadlily
Coptis occidentalis (Nutt.) T. & G.	goldthread
Epilobium angustifolium L.	fireweed
Epilobium paniculatum Nutt.	autumn willowweed
Xerophyllum tenax (Pursh) Nutt.	common beargrass

APPENDIX B

PREDICTING MINERAL SOIL EXPOSURE WITH USE OF THE DUFF REDUCTION TABLE

The percentage of the area burned bare to mineral soil in western larch/Douglas-fir forests can be predicted by using the following procedure

1. Take 100 or more duff depth measurements before burning, with the sample points scattered throughout the planned burn unit.
2. Decide the percentage of the area you desire to have burned bare to mineral soil. For an example, assume 60 percent bare is chosen.
3. List preburn duff depths taken. For example:

Duff depths (inches)

4
3
2
1
0
6
5
3
4
3

In this case there are only 10 measurements for the sake of keeping the example simple, so n=10. To have 60 percent of the area bare to mineral soil, six of these representative points must be reduced to zero depth.

4. Since duff tends to be consumed in a more or less uniform layer, examine the list to see how thick a layer must be burned off to bare 60 percent of the points. Proceed as follows:

1 point is zero, or 10 percent of the area sampled

2 points are 1 inch or less, or 20 percent of the area sampled

3 points are 2 inches or less, or 30 percent of the area sampled

6 points are 3 inches or less, or 60 percent of the area sampled.

Therefore a layer 3 inches thick must be burned away. Of course, some points do not have 3 inches of duff, but if a fire is prescribed that will consume 3 inches of duff, those with less will be bared along with those that have 3 inches.

5. Compute the percentage of loss for each point if 3 inches are removed, and average the result. If the preburn depth is less than 3, award that sample point 100 percent. With use of the example, proceed as follows:

$3 \div 4 = 0.75 \times 100 = 75\%$
$3 \div 3 = 1.0 \times 100 = 100\%$
2 100%
1 100%
0 100%
$3 \div 6 = 0.5 \times 100 = 50\%$
$3 \div 5 = 0.6 \times 100 = 60\%$
$3 \div 3 = 1.0 \times 100 = 100\%$
$3 \div 4 = 0.75 \times 100 = 75\%$
$3 \div 3 = 1.0 \times 100 = 100\%$

$$\text{Total} = 860$$
$$\text{Average} = \text{Total}/n = \frac{860}{10} = 86\%$$

Therefore, an 86 percent reduction in duff depth is needed to achieve exposure of mineral soil on 60 percent of the area.

6. Refer to table 2, reproduced here for convenience, to find the prescribed conditions for achieving 86 percent duff depth reduction. A measure of fuel loading on the area is necessary to determine if there are sufficient fuels to create a fire hot enough to consume the desired amount of duff. As stated earlier, expected fuel consumption can be predicted by multiplying the loading of small diameter fuels by 0.78. Then enter table 2 in the fuel consumption column closest to the result. For the example, assume a preburn weight of small fuels to be 20 tons per acre. Twenty x 0.78 = 15.6, so enter the table under the column headed 15 tons per acre. At this loading, it is possible to remove 90 percent of the duff if it is at 5 percent water content. Since the desired duff depth reduction is 86 percent, it is necessary to burn at a much higher duff water content, somewhere between 55 and 60 percent. Note, as discussed earlier, that the burning should be done when the water content of small fuels (not duff) is within the range of 10 and 17 percent.

Table 2.—Percentage of duff depth consumed predicted from duff water content and fuel consumption (from page 18)

Water content of lower half of duff layer	Tons per acre (t/ha) of small (<4 inch or <10 cm diam.) fuels consumed			
	5(11)	10(22)	15(34)	20(45)
Percent	*---Percentage of duff depth reduction----*			
5	60	78	90	100
10	59	78	90	100
15	57	78	90	100
20	55	77	90	100
25	53	77	90	100
30	51	76	90	100
35	48	74	89	100
40	46	73	89	100
45	43	70	89	100
50	41	68	88	100
55	39	65	87	100
60	36	61	85	100
65	34	58	83	99
70	32	54	80	99
75	30	49	77	98
80	28	45	73	97
85	26	41	69	96
90	24	36	64	95
95	22	32	59	94
100	21	29	53	92
105	19	25	47	89
110	18	22	41	86
115	17	19	36	82
120	15	17	31	78
125	14	15	27	73
130	13	14	23	68
135	12	13	21	62
140	11	12	19	56
145	11	11	17	50
150	10	11	16	44
155	9	11	16	38
160	9	10	16	34
165	8	10	15	30
170	8	10	15	27
175	7	10	15	24
180	7	10	15	23
185	6	10	15	22
190	6	10	15	21
195	6	10	15	21
200	6	10	15	21
205	5	10	15	21
210	5	10	15	21
215	5	10	15	21
220	5	10	15	21

APPENDIX C

SELECTED ANNOTATED BIBLIOGRAPHY: MILLER CREEK-NEWMAN RIDGE RESEARCH

Adams, D. F., and R. K. Koppe.

1969. Instrumenting light aircraft for air pollution research. J. Air. Pollut. Control Assoc. 19(6):410-415.

The airborne instrumentation package described measures and records up to 27 pollutant and flight variables. Real-time analysis instrumentation includes nondispersive infra-red analyzers for CO_2, CO, and hydrocarbons, conductivity and coulometric analyzers for sulfur dioxide and sulfur-containing gases, and a Charlson-Ahlquist visual range nephelometer. A Battelle "bulk sampler" is used to collect particulates. Air speed, altitude, rate of climb, magnetic heading, temperature, and relative humidity are continuously measured. All variables are recorded on magnetic tape. Tape data are reduced directly by IBM 360 computer to a digital printout or from tape to an X-Y analog plot.

Adams, Donald F., Robert K. Koppe, and Elmer Robinson.

1976. Air and surface measurements of constituents of prescribed forest slash smoke. *In* Proc. Int. Symp: Air Quality and Smoke from Urban and Forest Fires [Fort Collins, Colo. Oct. 1973]. p. 105-147. Natl. Acad. Sci., Washington, D.C.

Data from a ground-level network of air sampling stations, measurements of smoke plumes from the aircraft, and results from laboratory studies on burning tables are presented and discussed. Airborne particulate concentration near the ground surface was significantly raised at downwind locations on fire days. Dispersion of smoke at higher altitudes was measured through sampling of particulates and CO_2 in plumes from several fires with instruments aboard the aircraft.

Beaufait, William R.

1968. Scheduling prescribed fires to alter smoke production and dispersion. *In* Prescribed burning and management of air quality, Southwest Interagency Fire Counc. Proc. 1968:33-42.

The Northern Region-Intermountain Station cooperative study of the use of fire in silviculture is described. Instrumentation for data collection, especially that associated with Washington State University's air pollution research is discussed. Convection columns rose to a higher altitude and smoke plumes were more greatly dispersed from Miller fires when fuels were relatively dry and lapse rate was favorable than under the reverse conditions. To minimize smoke effects, fires should be scheduled when fuels are dry enough to create a strong convection column. Meteorological and fuel conditions required for adequate smoke dispersion can be made to correspond with those that achieve the objectives of land management through prescribing burning.

Beaufait, William R.

1971. Fire and smoke in Montana forests. *In* Forest land use and the environment. 23 p. Mont. For. and Range Exp. Stn., Sch. For., Univ. Mont., Missoula.

Fuel accumulates in most northern forests. Fire, playing its natural role, periodically removes this accumulation. The particulates in the smoke from these fires are an air pollutant of concern. Fires are inevitable; but their timing, severity, and dispersion of smoke from them are partially under man's control. The timing, duration, and severity of prescribed fires may be chosen and controlled so as to manage the direction and altitude of smoke plumes and thus avoid air pollution of downwind populated valleys. Nature's fuel management with wildfires does not permit this control.

Beaufait, William R., and Owen P. Cramer.

1969. Prescribed fire smoke dispersion-principles. USDA For. Serv., North. Reg., In-Serv. Rep., 12 p. Missoula, Mont. (Rev. Jan. 1972).

An illustrated presentation of the principles that must be considered in developing prescribed burning guidelines and in successfully conducting prescribed fires that result in efficient smoke dispersal.

Beaufait, William R., and William C. Fischer.

1969. Identifying weather suitable for prescribed burning. USDA For. Serv. Res. Note INT-94, 7 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Fire managers require continuous (24-hour) records of temperature, relative humidity, and windspeed to use fire efficiently and effectively. When carefully calibrated and interpreted, modified hygrothermographs provide the minimum instrumentation needed to obtain these records. An actual case of record interpretation and use is included.

Beaufait, William R., Charles E. Hardy, and William C. Fischer

1977 Broadcast burning in larch-fir clearcuts: the Miller Creek-Newman Ridge study. USDA For Serv. Res Pap. INT-175, rev., 53 p. Intermt For. and Range Exp. Stn., Ogden, Utah

Seventy-three clearcuts in western larch/Douglas-fir forests of western Montana were broadcast burned over a wide range of environmental conditions for the purpose of quantifying fire characteristics and burn accomplishment. The water content of the upper duff layer, and the National Fire-Danger Rating System Buildup Index (1964) were important predictors of both the heat pulse to the site and the amount of duff removed by the fire. The same two variables, along with the preburn weight of 1- to 10-cm diameter fuels, were the best predictors of the amount of fuel consumed by the fire.

Beaufait, William R., Michael A. Marsden, and Rodney A Norum.

1974. Inventory of slash fuels using 3P subsampling. USDA For. Serv. Gen. Tech. Rep. INT-13, 17 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

The large-scale study of prescribed broadcast burning in western Montana required development of a system to inventory clearcut logging slash fuels before and after fire treatment. The system is best suited for inventorying material that tends to be oriented parallel to the ground. The inventory system uses line intercept counts to compute volume, weight, and surface area of fuels. 3P subsampling is used to inventory twigs (0-1 cm diameter). Data reduction was accomplished with specially written computer programs. When used with proper and sufficient subsampling for collateral data, the system is well suited for the inventory of slash fuels in many forest types.

Brown, James K.

1970. Vertical distribution of fuel in spruce-fir logging slash. USDA For. Serv. Res. Pap. INT-81, 9 p. Intermt. for. and Range Exp Stn., Ogden, Utah.

About 70 percent of the volume and surface area of spruce-fir logging slash lies below the middepth of the slash. Material 0 to 1 centimeter in diameter was distributed vertically in the same proportions as all other material. Old slash in the first 20 centimeters above the ground contained a greater proportion of large material than new slash. Quantity of slash averaged 26.5 kg/m (118 tons/acre) dry weight with 0.57 kg/m composed of material 0 to 1 centimeter in diameter. Bulk density of slash decreased vertically and averaged 0.030 g/cm^3 for new slash and 0.053 for old slash. Needle mats suspended in the slash occurred with a 40 percent frequency.

DeByle, Norbert V.

1973. Broadcast burning of logging residues and the water repellency of soils. Northwest Sci. 47(2):77-87.

Pertinent literature is reviewed and summarized Water repellency of both organic and mineral soil horizons under larch and Douglas-fir were evaluated. The dry, decomposing litter was very water repellent. But probably because the underlying soil typically is moist when a prescribed fire is conducted, burning the slash did not alter the wettability of these medium- to fine-textured soils, even when the duff layer was almost entirely consumed. Burning of logging debris in the northern coniferous forest, if broadcast over the clearcut area, should not induce sufficient water repellency into medium- to fine-textured soils to be of concern. In contrast, the high temperatures reached at the soil surface beneath burned piles of slash or an intense wildfire on a dry soil mantle may induce water repellency, especially in coarse-textured soils.

DeByle, Norbert V., and Paul E. Packer.

1972. Plant nutrient and soil losses in overland flow from burned forest clearcuts. *In* Watersheds in transition. p. 296-307. Am. Water Resour. Assoc. Symp. Proc.

The results of physical and chemical analyses of the overland flow and sediment from 12 runoff plots at Miller and 12 at Newman are presented in detail. Logging and burning temporarily impaired watershed protection and increased overland flow and erosion, especially on the steep slopes at Newman. However, vegetal recovery returned conditions to near prelogging status within 4 years. There was an increase in plant nutrient losses in both the sediment and in the overland flow during the denuded period; but it represented only a small fraction of the nutrient capital.

DeByle, Norbert V.

1976. Fire, logging, and debris disposal effects on soil and water in northern coniferous forests. Proc. XVI IUFRO World Congr., Oslo, Norway, 1976:201-212.

The author explains why under some conditions clearcutting or fire has severe impacts on the environment and why under other conditions impacts are minimal or not even detectable. The variables of soils, geology, topography, climate, and forest type are considered.

DeByle, Norbert V.
1976. Soil fertility as affected by broadcast burning following clearcutting in Northern Rocky Mountain larch/fir forests. Fire and Land Manage. Symp. [Missoula, Mont., Oct. 8-10, 1974]. *In* Proc. Tall Timbers Fire Ecol. Conf. 14:447-464.

Plant nutrient content and associated soil parameters were determined under 35 monitored burns of broadcast logging debris at Miller Creek in western Montana. The duff or ash-duff mixture and four increments to a 30 cm depth into mineral soil were sampled before, immediately after, and for up to 2 years after burning. Data are reported for pH, cation exchange capacity, organic matter, nitrogen, phosphorus, potassium, sodium, calcium, and magnesium. Burning volatilized a third of the nitrogen in the organic surface horizon. Leaching and erosion of the surface ash-duff layer during the next 2 years markedly reduced its nutrient content. The pH and the content of some available nutrients in the underlying mineral soil increased. Most nutrients leached from the surface probably were held beneath in the relatively fine textured mineral soils.

Fiedler, Carl E.
1974. Atmospheric conditions surrounding a seedfall in western Montana. M.S. thesis. Sch. For., Univ. Mont., Missoula. 46 p.

Wind movement over two clearcuts of opposing aspect and the intervening ridge was studied. Continuous data on windspeed and direction were taken at three locations. A series of tethered weather balloons along the clearcut edges provided supplemental data. Movement of these balloons with changing wind patterns was recorded with time lapse photography. Dispersal of smoke from smoke grenades was also photographed. Wind behavior on opposite aspects and the ridgetop and likely effects on seed dissemination are discussed.

Fischer, William C., William R. Beaufait, and Rodney A. Norum.
1969. The hygrothermoaerograph—construction and fire management application. USDA For. Serv. Res. Note INT-87, 8 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Conventional hygrothermographs can be modified to record windspeed along with temperature and relative humidity. The fire-weather record resulting from the modification has application in prescribed fire planning, fire-danger rating, fire-weather forecasting, fire-behavior analysis, and fire-weather climatology.

Flaherty, David C.
1967 Better burns..and better air? Quest, Dec. 1967:16-21. Wash. State Univ., Pullman.

This article, written in popular style, summarizes the objectives of the Miller Creek study and highlights the air pollution research of Washington State University.

Flaherty, David C.
1972. Are we objective about forest fires? Am. For. 78(9):12-15, 58-59.

This popular article concerning fire's role in the environment is based on an interview with W. R. Beaufait. Beaufait explains why fire is a natural component of the Northern Rocky Mountain forests. He describes how the Northern Region-Intermountain Station cooperative studies contribute to a better understanding of the use of fire in silviculture.

Koppe, Robert K., and Donald F. Adams.
1969. Dispersion of prescribed fire smoke. Pap. 69-AP-36, 21 p. Wash. State Univ., Pullman.

Results of airborne sampling for aerosols and carbon dioxide in the smoke plumes of two typical prescribed fires at Miller are described. The major portion of one plume was transported downwind at 3950 m altitude at a rate between 15 and 21 m/sec, near that of the calculated windspeed at that elevation. There was excellent correlation between smoke particles and carbon dioxide concentration for 25 km downwind from prescribed fires, where carbon dioxide level in the diffusing plume was approximately 10 percent above background. From 25 to 55 km downwind the carbon dioxide concentration in the plume and the background were comparable, although the boundary of the plume was clearly discerned by the sampling instruments. Aerial intercepts of the edge of the convection column during the initial buildup phase of the fire revealed carbon dioxide concentrations up to 500 parts per million.

Malte, P.C.
1975. Pollutant production from forest slash burns. Wash. State Univ., College Eng. Bull. 339, 32 p.

The percentage of slash fuel converted to smoke is presented for three Newman fires. Concentrations of particulate matter and CO_2 were determined with airborne sampling devices. Fuel inventories, moisture content data, elemental analyses for C/H/N, and burning table results were also utilized. Relatively dry forest slash

composed primarily of Douglas-fir and larch, with moisture contents of approximately 5 percent for needles, 10 percent for twigs, and 30 percent for the forest-floor duff, gave mass ratios of pollutant to burned material (including moisture) of approximately 1 4 for CO_2, 0.016 for particulate, 0.12 for CO, and 0 008 for NO_2. For one fire, the particulate/CO_2 ratio increased markedly as the fire grew during the first hour. Another fire plume gave a steady, apparently maximum, particulate/CO_2 ratio of 0 014 at the 1-hour point.

Norum, Rodney A.
1970. Probable smoke column heights from slash fires. M.S. thesis Sch. For., Univ. Mont., Missoula, 65 p.

This is a more detailed report of the material presented in the following cited Research Paper INT-157.

Norum, Rodney A.
1974. Smoke column height related to fire intensity. USDA For. Serv. Res. Pap. INT-157, 7 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

The ultimate height of slash-fire smoke columns is strongly related to fire intensity and only loosely related to lapse rate and other measures of atmospheric stability By conducting intense firés, managers can maintain air quality when atmospheric conditions are less than ideal for smoke dispersal.

Packer, Paul E.
1972. Site preparation in relation to environmental quality. *In* Proc. 1971 Annu. Meet. West. For. and Conserv. Assoc., Portland, Oreg. p. 23-28.

Current knowledge is summarized about objectives and methods of site preparation for forest regeneration in relation to environmental quality. The author discusses disposition of logging residue, redution or elimination of plant competition, preparation of mineral soil seedbeds, and provision of favorable microenvironment. Effects of prescribed fire, chemical treatment, and various mechanical methods of site preparation in realtion to air and water pollution are covered.

Packer, Paul E., and Bryan D. Williams.
1976. Logging and prescribed burning effects on the hydrologic ano soil stability behavior of larch/Douglas-fir forests in the northern Rocky Mountains. Fire and Land Manage. Symp. [Missoula, Mont., Oct. 8-10, 1974]. *In* Proc. Tall Timbers Fire Ecol. Conf. 14:465-479.

The soil and hydrologic changes that occurred on 12 runoff plots at Miller for 7 years after treatment are described. There was a moderate increase in runoff and erosion following clearcutting and broadcast burning, primarily due to reduction of protective cover at or near the mineral soil surface. On all but south-facing slopes recovery was rapid, with runoff and erosion values returning to essentially pretreatment levels in less than 7 years. South slopes, with more intense burns and harsher site conditions, are slower to reċover; here less drastic treatment is recommended.

Shearer, Raymond C.
1975. Seedbed characteristics in western larch forests after prescribed burning. USDA For. Serv. res. Pap. INT-167, 26 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Establishment of western larch seedlings is favored by site preparation that reduces the duff layer and sprouting of competing vegetation. The effectiveness of prescribed broadcast burning for seedbed preparation during the months of May through October was studied on clearcuts on all aspects at Miller Creek in northwest Montana. Greatest duff reduction, root mortality, and soil heating occurred when duff and soil water contents were lowest. Duff on north-facing slopes dries more slowly than on other aspects, requiring that the slash be burned in summer when the duff is dry to reduce the organic mantle and to prepare a satisfactory seedbed. Summers of frequent rainfall may prevent satisfactory preparation of seedbeds on north slopes. East-, south-, and west-facing slopes have a wider range of time when burning will prepare seedbeds suitable for natural regeneration.

Shearer, Raymond C.
1976. Early establishment of conifers following prescribed broadcast burning in western larch/Douglas-fir forests. Fire and Land Manage. Symp. [Missoula, Mont., Oct. 8-10, 1974]. *In* Proc. Tall Timbers Fire Ecol. Conf. 14:481-500.

Broadcast burning that reduced duff to within 1 cm of the mineral soil at random intervals provided seedbed conditions favorable for establishment of conifer regeneration in clearcuts at Miller and Newman. The interactions of seedbed condition, seed dispersal, and seed and seedling mortality are discussed in relation to natural regeneration. Seed-seedling ratios for several conifer species show relative regeneration success by aspect and habitat types. North- and east-facing slopes usually were quickly regenerated by coni-

fers. South- and west-facing slopes require protection by shade to enhance conifer establishment.

Stickney, Peter F.
1980. Data base for post-fire succession, first 6 to 9 years, in Montana larch-fir forests. USDA For. Serv. Gen. Tech. Rep. INT-62, 133 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Baseline data on plant species cover (m^2/0.01 ha) and volume of space occupied (m^3/0 01 ha) for the initial 6 to 9 years of secondary forest succession following wildfire or clearcutting and broadcast slash burning are presented in tabular form for 20 larch/Douglas-fir sites in western Montana. Location, physical description, predisturbance stand, and details of disturbance are given for each site. These data, presented without interpretation, are available for analytical use by others in forest development modeling and forest management application.

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DeByle, Norbert V.

1981. Clearcutting and fire in the larch/Douglas-fir forests of western Montana—a multifaceted research summary. USDA For. Serv. Gen. Tech. Rep. INT-99, 73 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Logging slash on 73 clearcuts was broadcast burned over a wide range of conditions, achieving a broad array of fire intensities and effects. An intense wildfire was also evaluated. Fire effectiveness was measured and related to preburn conditions and fire intensity. Treatment effects on air quality, forest regeneration, vegetation recovery and development, small mammal populations, soil physical and chemical parameters, and runoff and erosion were measured and analyzed.

KEYWORDS: fuel reduction, fire effects, broadcast burning, fire intensity, forest regeneration, logging slash